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REFERENCES

Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, 25¢.)

Stearns, H. T., 1945a. Glaciation of Mauna Kea, Hawaii: Geol. Soc. America Bull., vol. 56, pp. 267-274.

———, 1945b. Late Geologic history of the Pacific basin: AM JOUR. SCI., vol. 243, pp. 614-626.

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THE BASE OF THE CAMBRIAN IN THE SOUTHERN APPALACHIANS

PHILIP B. KING

PART 1

ABSTRACT. The Cambrian differs from all other systems that succeed it in that its base is undefined paleontologically, for the Cambrian is underlain by stratified rocks without fossils. Recent publications have indicated considerable diversity of opinion as to the proper position of the base of the system.

As a contribution to the solution of the problem, the writer in this paper examines the stratigraphy of beds that have been assigned to the pre-Cambrian and early Cambrian in a typical area—the southern Appalachians. The oldest Lower Cambrian fossils in the area occur in the upper part of the Chilhowee group. This group is a sequence of clastic rocks 2,500 to 7,500 feet thick, having closely related characters from base to top, and probably formed during a single depositional cycle. It is interpreted as the initial deposit of the miogeocyncline in which the Cambrian and Ordovician rocks now exposed in the Appalachian Valley were deposited. Underlying the Chilhowee group locally are the Catoctin greenstone and its associated sedimentary rocks, the volcanics of the Mount Rogers area, and the Ocoee series. These rock units were formed under conditions of considerable crustal instability. and differ greatly in character from the formations of the Chilhowee group. The Catoctin greenstone and the volcanics of the Mount Rogers area are separated from the Chilhowee group by erosional unconformities; an unconformity may also exist between the Ocoee series and the Chilhowee group. All three of the rock units below the Chilhowee group rest with profound unconformity on ancient plutonic rocks.

It is concluded that there is a reasonable physical basis for drawing the base of the Cambrian in the southern Appalachians at the base of the Chilhowee group, even though the oldest Cambrian fossils appear well above this horizon. The unconformity at the base of the Catoctin greenstone, the volcanics of the Mount Rogers area, and the Ocoee series—does not mark the base of the Cambrian but lies within the pre-Cambrian, serving to divide the pre-Cambrian rocks of the area into two parts of considerably different age.

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[1] Published by permission of the Director, Geological Survey, U. S. Department of the Interior.

[2] While the present manuscript was passing through the hands of the Geological Survey editors, the following publication appeared: Stose, G. W., and Stose, A. J., 1949, Ocoee series of the southern Appalachians. Bull. Geol. Soc. Am., **60**, 267-320. After reviewing this publication the writer concludes that it contains nothing which requires specific comment at this time, or necessitates modification of the conclusions presented in the present paper.

STATEMENT OF PROBLEM

THE Cambrian differs from all other systems that succeed it in that its base is undefined paleontologically. At the boundaries of all succeeding systems, the faunas of one give place to those of the next, and however much the precise boundary may be debated, it is debated with knowledge of the faunas of the beds involved. In the Cambrian system, the lowest fossil zone is underlain by strata without fossils, or with fossils of so ambiguous a nature as to be useless for precise paleontological zonation.

Years ago, referring to the base of the Cambrian, Walcott (1891, p. 389) asked:

> "Is the basal line of the Cambrian group at the lowest limit at which the *Olenellus* fauna is found? Where this lowest limit occurs at the base of a conformable series resting unconformably upon pre-Cambrian rocks there is no difficulty in answering the question. But where it occurs in the midst of a conformable series and there remain thousands of feet of sediments beneath the *Olenellus* zone, as in Nevada and Utah, it still remains a problem for consideration."

The position of the base of the Cambrian system is not in dispute in widespread continental areas where Cambrian strata younger than the *Olenellus* zone lie on the eroded surface of much older igneous or metamorphic rocks of obvious pre-Cambrian age. But in geosynclinal areas such as those in the Appalachian and Cordilleran provinces, the fossiliferous Lower Cambrian is underlain in many places by unfossiliferous sedimentary or volcanic rocks. In the geosynclines, the questions posed by Walcott remain in dispute to this day.

Recent publications reflect the current state of uncertainty on the problem, and revisions of classifications commonly employed have been proposed by various geologists. However, these geologists are not in agreement among themselves, for some wish to place the base of the Cambrian higher, and others lower than the boundary commonly employed.

The Cambrian correlation chart, prepared by a subcommittee of the Committee on Stratigraphy of the National Research Council (Howell and others, 1944), shows at the bottom the lowest formation that contains diagnostic Cambrian fossils, but does not show other formations beneath, even though these

are also conventionally classed as Cambrian. Snyder (1947, p. 152) and Wheeler (1947, pp. 157-159) express approval of this procedure, and recommend that the base of the Cambrian be placed either at the base of the lowest formation containing Cambrian fossils, or immediately beneath the lowest occurrence of Cambrian fossils.

By contrast, Bloomer and Bloomer (1947, pp. 102-106) conclude that the volcanics and underlying sedimentary rocks in Virginia are of Cambrian age, even though they lie some distance beneath fossiliferous Cambrian strata and have been classed conventionally as pre-Cambrian. This conclusion is based on a lithologic similarity between beds hitherto classed as Cambrian and as pre-Cambrian, and on a lack of certain unconformity between them. Likewise, Furcron and Teague (1947, pp. 19-21) conclude that the unfossiliferous Ocoee series of northern Georgia, hitherto variously classed as Cambrian or pre-Cambrian, is actually Cambrian because it rests unconformably on older granites and gneisses.

PURPOSE OF THIS PAPER

The southern Appalachians is one of the critical areas in which the problem of the position of the base of the Cambrian comes to the fore, and conclusions drawn on the basis of study of this area have a bearing on the general solution. In the present paper, the writer proposes to examine the stratigraphy of those beds in this region that have been classed as pre-Cambrian and early Cambrian, and to offer some tentative suggestions as to their classification. The paper is an outgrowth of work in progress and ideas in process of evolution. It states a thesis which will be elaborated and perhaps modified as this work proceeds.

During the past eight years (1940-1948) the writer has participated in three field projects of the U. S. Geological Survey, involving study of older rocks of the southern Appalachians: (1) Near Elkton, in Page and Rockingham Counties, northern Virginia, for a distance of 20 miles along the strike of the rocks in the northwestern foothills of the Blue Ridge (King, 1943, 1947) (fig. 1). (2) In Johnson, Carter, and Unicoi Counties, northeastern Tennessee, for a distance of 40 miles along the strike of the rocks in Iron, Holston, and Unaka Mountains (King and others, 1944). (3) Near Gatlinburg, in Blount and Sevier Counties, east-central Tennessee,

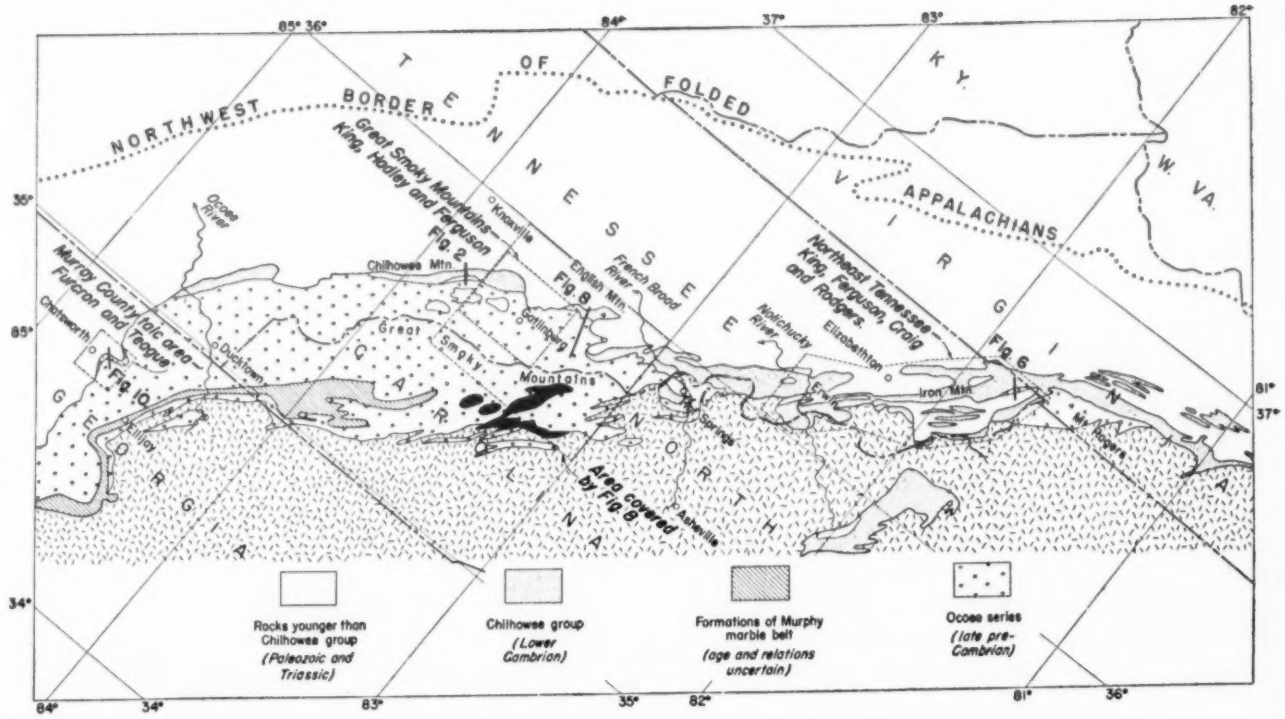
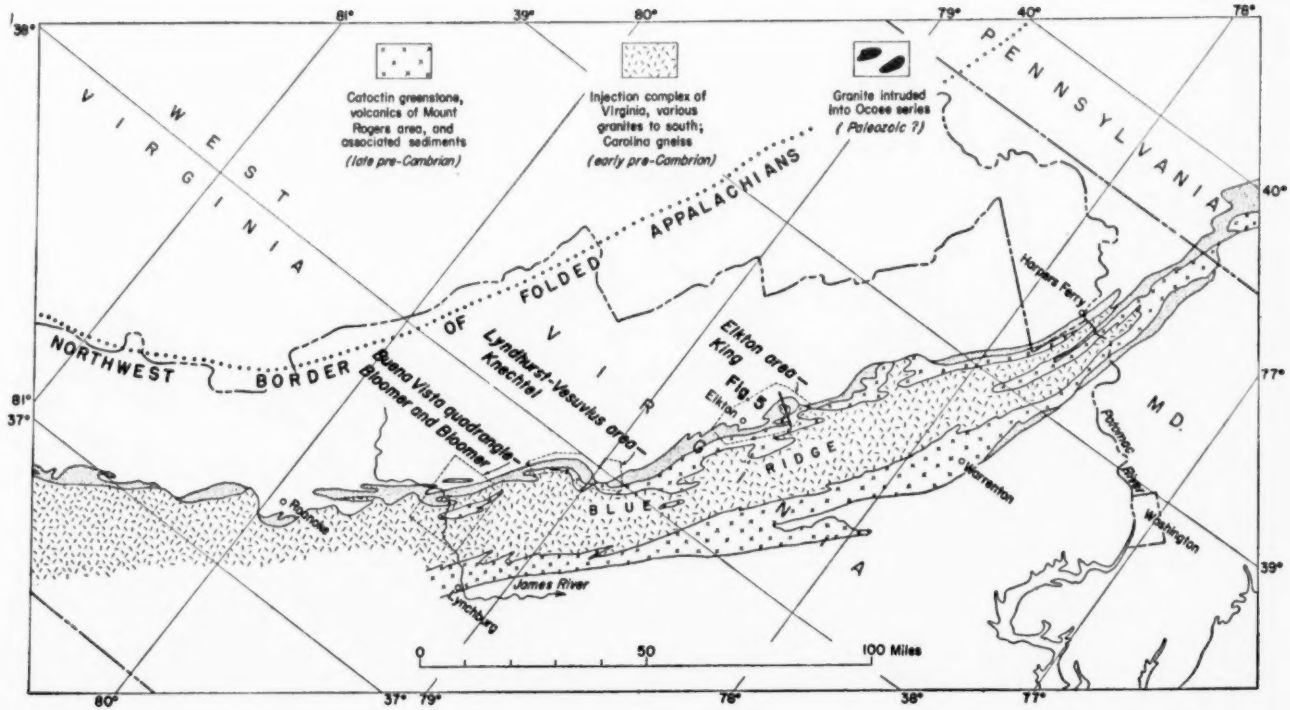


Figure 1. Sketch map of parts of Virginia, Tennessee, and North Carolina, showing outcrops of units of early Cambrian and late pre-Cambrian age, and location of places mentioned in text. Areas enclosed in rectangles have been covered in recent geologic investigations that are referred to in text.


Catoctin greenstone, volcanics of Mount Rogers area, and associated sediments (late pre-Cambrian)
Injection complex of Virginia, various granites to south; Carolina gneiss (early pre-Cambrian)
Granite intruded into Ocoee series (Paleozoic ?)
WEST VIRGINIA
PENNSYLVANIA
FOLDED APPALACHIANS
NORTHWEST BORDER
Buena Vista quadrangle—Bloomer and Bloomer
Lyndhurst-Vesuvius area—Knechtel
Elkton area—King
Fig. 5
Elkton
Harpers Ferry
Potomac River
Warrenton
Washington
Roanoke
BLUE RIDGE
James River
Lynchburg
MD.
0
50
100 Miles
38°
81°
37°
80°
39°
80°
79°
40°
78°
40°
77°
39°
37°
79°
78°
38°
77°

for a distance of 22 miles along the strike of the rocks in the Great Smoky Mountains and Chilhowee Mountain. This last investigation is now in progress. These areas are widely scattered, but each is a representative sample of the broader district of which it forms a part. The writer's knowledge of inter-

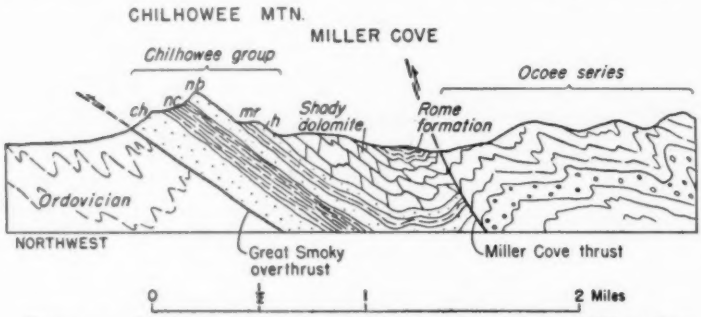


Figure 2. Structure section of Chilhowee Mountain and Miller Cove, Blount County, Tennessee, showing type section of Chilhowee group. Formations of Chilhowee group are indicated by abbreviations as follows: ch—Cochran conglomerate, nc—Nichols shale, nb—Nebo quartzite, mr—Murray shale, h—Hesse quartzite. After Keith, with modifications by the writer.

vening areas is based on field excursions and on a review of published papers.

During the investigations in the southern Appalachians the writer has been associated, among others, with John Rodgers of Yale University, H. W. Ferguson of the Tennessee Division of Geology, and J. B. Hadley of the U. S. Geological Survey. Some of the field facts given in this paper were determined by them rather than by the writer, and others were determined jointly in their company in the field. Interpretations and conclusions given here have been discussed with them, both before and during preparation of this paper, but the theses presented herein are the writer's own, and are not necessarily shared by his colleagues.

CHILHOWEE GROUP

Terminology.—One of the most widespread units of the southern Appalachians is the Chilhowee group, named by Safford (1856, pp. 152-153; 1869, pp. 198-203) for Chilhowee Mountain, Blount and Sevier Counties, east-central Tennessee (fig. 2).[3] The group underlies the Cambrian and Ordovician

[3] Problems relating to usage of the term Chilhowee group are discussed under the heading "Notes on terminology" at the end of this paper.

carbonate rocks (Shenandoah limestone of early reports) of the Appalachian geosyncline, which form the Appalachian Valley. The Chilhowee group consists of clastic rocks 2,500 to 7,500 feet thick that stand as ridges and mountains southeast of the valley (fig. 1). Representatives of the group occur in Tennessee and Virginia, and equivalents extend southwest into Alabama and northeast beyond Pennsylvania. The Chilhowee is conventionally classed as the lowest unit of the Lower Cambrian series.

The Chilhowee group has been subdivided into different sets of formations in its several areas of exposure; these variations in terminology obscure the essential unity of the group, the wide extent of its characteristic rock types, and the similarity of sequence in all sections. The terminology in three principal areas of outcrop is indicated in table 1.

TABLE 1

Formations of the Chilhowee group in Tennessee and Virginia[4]

		East-central Tennessee (Chilhowee Mountain)	Northeastern Tennessee (Johnson, Carter and Unicoi Counties)	Northern Virginia (Elkton and Harpers Ferry areas)
Lower Cambrian		Shady dolomite (in Miller Cove)	Shady dolomite	Tomstown dolomite
	Chilhowee group	Hesse quartzite	Erwin quartzite	Antietam quartzite
		Murray shale		
		Nebo quartzite		
		Nichols shale	Hampton shale	Harpers shale
		Cochran conglomerate	Unicoi formation (with basalt flows 1000–1500 feet below top)	Weverton quartzite
				Loudoun formation (with tuffaceous slate and rare flows)
Pre-Cambrian		Ocoee series	Volcanics of Mt. Rogers area	Catoctin greenstone Swift Run formation
			Cranberry granite	Injection complex

[4] See also "Notes on terminology" at the end of this paper.

Fossils.—Fossils are found sparingly in the upper part of the Chilhowee group. Small collections of trilobites and brachiopods have been made from the topmost beds, that is, from calcareous sandstones at the top of the Hesse, Erwin, and Antietam quartzites (Butts, 1940, p. 40). These fossils include *Olenellus* and are of Lower Cambrian age. In addition, Keith (1895, p. 3) reported the occurrence of trilobites and brachiopods at a horizon nearly 500 feet lower, at two localities ascribed to the Murray shale of Chilhowee Mountain: (1) On the east side of Little River Gap, and (2) on the crest of the mountain above Montvale Springs. The first of these stations is of doubtful stratigraphic position and may well be in the top beds of the Chilhowee group (Stose and Stose, 1944, p. 388), but the second is almost certainly in the Murray shale and represents the oldest recorded occurrence of trilobites and brachiopods in the southern Appalachians. Most of the fossils from the Chilhowee group were collected years ago by Walcott (1891, p. 302; 1892; 1892A) and further detailed search might yield other localities and horizons, as well as greater knowledge of these oldest Cambrian faunas.

Besides the trilobites and brachiopods, the Chilhowee group contains other indications of life—*Scolithus*, or probable worm tubes. These occur at approximately the same level as the trilobites and brachiopods, but also extend for a considerable distance beneath them. The tubes are exceedingly abundant in parts of the Antietam and Erwin quartzites (Stose and others, 1919, pp. 16-17; King and others, 1944, pp. 30-31). In the Erwin, they are especially abundant in white quartzite beds in the lower part of the formation. They are similarly abundant in the Nebo quartzite. *Scolithus* also occurs in indurated sandstone beds in the Hampton and Harpers shales. It is absent in the lower formations of the Chilhowee group.

Conditions of deposition.—The Chilhowee group is a conformable sequence of beds, formed during a single depositional cycle, with no great difference in age between its component parts. All sections possess a similar upward sequence of deposits. The most distinctive parts of the group, the coarse clastics, change from arkosic sandstones and arkosic conglomerates below (in the Cochran, Unicoi, and Weverton

formations) to fine-grained, indurated, quartzose sandstones (generally termed "quartzites") above (in the Nebo, Hesse, Edwin, and Antietam formations).[5] The conglomerates of the lower beds contain rounded pebbles and granules of quartz and other resistant constituents of older rocks, but these are absent above. Cross bedding ("current bedding" of British geologists) is common, and ripple marks are not rare. Sediments of the Chilhowee group were probably derived from lands of moderate relief, which by the end of Chilhowee time had probably been peneplaned. Sediments of the Chilhowee group are the initial deposits of the miogeosyncline (Kay, 1947, p. 129) in which the Cambrian and Ordovician rocks now exposed in the Appalachian Valley were deposited.

The occurrence of fossils in the Chilhowee group is closely related to the sequence of sediments: the lower arkosic and conglomeratic part is barren; the middle part, with its quartz sand deposits contains only *Scolithus*; and the upper part, laid down in the waning stages of sand deposition contains trilobites and brachiopods. This relation so closely resembles the relation in later transgressive deposits as to suggest that the appearance of diagnostic fossils in the upper part of the Chilhowee group is due, not to any abrupt evolutionary development, but to migration of marine life into the region in response to an increasingly more favorable environment.

A distinctive feature of the Chilhowee group is the presence of volcanics which occur in some areas. In northeast Tennessee and southwest Virginia the Unicoi formation, the basal formation of the group, contains flows of amygdaloidal basalt and associated tuffaceous shales and sandstones (fig. 6) (King and others, 1944, pp. 39-40; Butts, 1940, pp. 27-31). Great variations in the volcanics of the Unicoi may be observed both along the strike and between different outcrop belts. In places, two or more volcanic beds are present, each 100 or more feet thick; in others a single thin bed is present; in others volcanic rocks are lacking. The volcanics in the Unicoi pinch out not far southwest of the Nolichucky River in Tennessee, and are absent from the Unicoi and its stratigraphic equivalent, the Cochran conglomerate, farther southwest. These variations

[5] For explanation of rock names used, see "Notes on terminology" at end of this paper.

arise from the expectable conditions of a volcanic episode.[6]

In northern Virginia at the base of the Chilhowee group are tuffaceous spotted slates and rare thin beds of lava (Furcron and Woodward, 1936). These volcanics are a part of the Loudoun formation (Stose and Stose, 1946, pp. 31-34); in the Elkton area they comprise the whole of the formation, but near the Potomac River they are interbedded with sandstone and arkose. In the Buena Vista quadrangle to the southwest, volcanics also form the base of the Chilhowee group (Bloomer and Bloomer, 1947, p. 103) and may be the same unit as the Loudoun, although they are there termed "the basal portion of the Unicoi."

Correlation within the Chilhowee group.—The top of the Chilhowee group or its contact with the overlying Shady and Tomstown dolomites, seems to be a well-defined time horizon of about the same age everywhere, and expresses a marked, widespread change in sedimentation (table 1). Correlation of the underlying parts of the group is less certain. The Unicoi of northeastern Tennessee usually has been correlated with the Loudoun and Weverton of northern Virginia, the Hampton with the Harpers, and the Erwin with the Antietam. All these units are lithologic, and are merely the local expression of upward changes in sedimentation during Chilhowee time, such as that from arkosic sandstone and conglomerate below to quartz sandstone above.

There is no assurance that these lithologic units were laid down at the same time in all areas. The Chilhowee group thins from a maximum of 7,500 feet in parts of Tennessee to 2,500 feet near the Potomac River in northern Virginia. Conceivably the Weverton quartzite, or northern representative of the arkosic sandstone facies, might have been deposited at a later time than the Unicoi, or southern representative of the same facies (fig. 3B).

The volcanics of the Chilhowee group afford some clue as to correlation within the group. The volcanics in the Unicoi formation of northeast Tennessee are quite variable from one local outcrop to another, but they culminate in a zone that

[6] On these grounds, the writer disagrees with Stose and Stose (1944, p. 389) who state, "With the present knowledge, it is not possible to decide which formation, if any, in the Chilhowee type section represents the Unicoi formation, but *it is evident that the lower part of that formation which contains the basalt flows is not present* because neither Hayes nor Keith describe such flows in the section" (italics the present writer's).

is 1,000 to 1,500 feet below the top of the Unicoi, or 4,000 to 4,500 feet below the top of the Chilhowee (they are hereafter referred to as the "main volcanic zone" of the Unicoi; "main basalt" of fig. 6). Those in the Loudoun formation of northern Virginia are at the base of the Chilhowee group and 2,500 feet

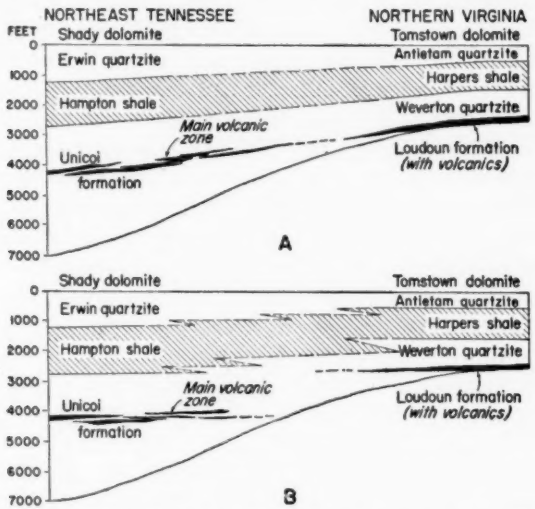


Figure 3. Stratigraphic diagrams between northeast Tennessee and northern Virginia, indicating possible correlations: (A) on the assumption that the volcanics in the two areas are of the same age, and (B) on the assumption that they are of different ages.

below its top. The writer believes that the volcanics of the Unicoi express an episode of regional time significance, and he suggests that those of the Loudoun formation are of approximately the same age. If this correlation is accepted, the Weverton, Harpers, and Antietam are probably the thinned equivalents respectively of the upper Unicoi, the Hampton, and the Erwin (fig. 3A), rather than a similar facies of later age (fig. 3B).

By either of the interpretations just suggested, the sediments below the main volcanic zone of northeast Tennessee, classed as a lower part of the Unicoi formation, are older than any part of the Chilhowee group of northern Virginia, and are not represented there. As no unconformity is known between them and the upper part of the Unicoi, they seem to be a part of the Chilhowee depositional cycle. These lower beds

may therefore pass out by overlap toward the northeast. Further comment on these beds is made below.

Correlation between formations of the Chilhowee group of northeast Tennessee and those of Chilhowee Mountain farther southwest will now be considered. No special problems seem to be involved in the beds above the Cochran conglomerate and Unicoi formation, and relations as indicated in table 1 may be regarded as reasonably well established. The Nebo quartzite of Chilhowee Mountain, for example, bears abundant *Scolithus* as does the apparently equivalent lower member of the Erwin quartzite of northeast Tennessee.[7] Also, H. W. Ferguson (personal communication, 1948) has found in the Nichols shale at a few places near the northeast end of Chilhowee Mountain the same characteristic arkosic sandstones that occur interbedded in the Hampton shale of northeast Tennessee.

More uncertainty exists as to correlation of the Unicoi formation and the Cochran conglomerate. In northeast Tennessee, Keith (1907A, p. 5 and areal geology sheet) placed the equivalent of the Cochran high in the section, at some localities in what is classed by King and others (1944) as upper Unicoi, in others as lower Hampton. Lower beds of the Unicoi were correlated with the Snowbird formation and Hiwassee slate, here regarded as units of the Ocoee series. The Cochran is an arkosic sandstone and conglomerate of the same facies as the upper part of the Unicoi. It is reported to be 1,100 to 1,700 feet thick on Chilhowee Mountain (Keith, 1895, p. 3), but exceeds 2,500 feet near the French Broad River to the east (Keith, 1904, p. 5; H. W. Ferguson, personal communication, 1948).

Sections of the Unicoi formation in northeast Tennessee show wide variations in thickness and considerable differences in lithology, especially within the strata below the main volcanic zone, classed as the lower part of the Unicoi—a variation emphasized by the piling up of thrust sheets, and the consequent juxtaposition of masses of Unicoi originally deposited far apart. Beds originally laid down farthest to the northwest are exposed along the Nolichucky River southeast of Erwin (fig. 1) and along the Doe River south of Hampton 20 miles

[7] In a recent paper Stose and Stose (1947, p. 629) interpret the Nebo as equivalent to the upper part of the Unicoi of northeast Tennessee, but there is little basis for this view.

to the northeast. At these places the Unicoi is 2,000 to 2,500 feet thick and includes 1,000 feet or more of beds older than the main volcanic zone. These lower strata are arkosic sandstones very much like the upper strata, and the whole unit is probably equivalent to the Cochran. The possibility seems remote that any of it is equivalent to the Snowbird or other formations of the Ocoee series, as suggested by Keith (1907A).

Other occurrences of the Unicoi formation in northeast Tennessee, notably those of Iron Mountain (fig. 1), represent parts of the farther traveled thrust sheets, and show thicknesses of Unicoi of as much as 5,500 feet (fig. 6). On Iron Mountain, the beds below the main volcanic zone consist "largely of thin-bedded arkosic siltstone and sandstone, but layers of red and green clay shale and poorly indurated conglomerate are also present" (King and others, 1944, p. 40). These beds possess more of a graywacke facies than an arkosic sandstone facies and, as pointed out by Stafford (1869, pp. 195-196) resemble the rocks of the Ocoee series. At least the lower part of these beds is probably older than the type Cochran conglomerate, as well as of the Loudoun formation and Weverton quartzite to the northeast. Whether any of them is equivalent to the true Ocoee series farther southwest is problematical.

CATOCTIN GREENSTONE AND UNDERLYING SEDIMENTARY ROCKS

In northern Virginia, and in Maryland and Pennsylvania as well, the most prominent formation beneath the Chilhowee group is the Catoctin greenstone[8] (Keith, 1894, pp. 306-309), a series of thick, massive lava flows and associated agglomerates, tuffs, and tuffaceous slates. The Catoctin has generally been classed as a metabasalt (Furcron, 1934, pp. 401-404; Stose and Stose, 1946, pp. 20-22), but in the Buena Vista quadrangle Bloomer and Bloomer (1947, p. 97) have identified it as a propylite, or altered andesite. In northern Virginia, Maryland, and Pennsylvania, the greenstone is interbedded with flows of rhyolite and andesite (Keith, 1894, pp. 302-306; Stose and Stose, 1946, pp. 22-24).

The Catoctin greenstone is nearly everywhere underlain by sedimentary formations of variable thickness which include the Swift Run formation from Elkton north to the Potomac River (Stose and Stose, 1946, pp. 18-20; King, 1947),

[8] See "Notes on terminology" at end of this paper.

and its probable correlatives — the Fauquier formation of Furcron (1939, pp. 37-41) in the Warrenton area, and the Oronoco formation of Bloomer and Bloomer (1947, p. 95) in the Buena Vista area (fig. 1).

Bloomer and Bloomer (1947, p. 103) report that "without the aid of field relations it is difficult if not impossible to distinguish the rocks of the Oronoco formation from those in the lower part if the Unicoi formation." By contrast, the Swift Run formation of the Elkton area is greatly different from the younger Weverton quartzite. Both the Swift Run and Weverton include much arkosic sandstone, but the most prominent detrital constituents of the Swift Run formation are pink feldspar and epidote, derived from the injection complex beneath it and lacking in the Weverton. Quartz grains and pebbles, including much "blue" quartz, are more prominent in the Weverton quartzite than in the Swift Run formation. The two formations seem to have been laid down under different geographic conditions, and may have been derived from different sources.

The relation of the Catoctin greenstone and underlying sedimentary rocks to the plutonic rocks of the injection complex has been much disputed. Keith (1894, pp. 314, 318) interpreted the injection complex as intrusive into the Catoctin, and this view has been reaffirmed by Furcron (1934, pp. 405-410) and Cloos (Cloos and Hietanen, 1941, pp. 80, 83, fig. 29). However, Jonas and Stose (1939, pp. 579-580) and Bloomer and Bloomer (1947, pp. 95-97) consider that the Catoctin and the underlying sedimentary rocks lie unconformably on the injection complex. The latter view has been confirmed by the writer's own observations in the Elkton area (King, 1947). Many outcrops were found, of which the most accessible is on the south side of the East Branch of Naked Creek a mile east of Jollett (fig. 4), which display the rocks of the Swift Run formation lying unconformably on the eroded surface of the injection complex. The indurated sandstones of the Swift Run formation of the Elkton area contain minerals derived from the erosion of the injection complex. The Swift Run persists throughout the Elkton area as a nearly continuous stratum 50 or 100 feet thick between the Catoctin above and the injection complex below, an unlikely relation if the latter were intrusive into the former.

The Catoctin greenstone and underlying sedimentary rocks thin out in places, so that the overlying Chilhowee group overlaps them and lies directly on the injection complex. This relation was observed by Stose and Stose (1946, pp. 28-29)

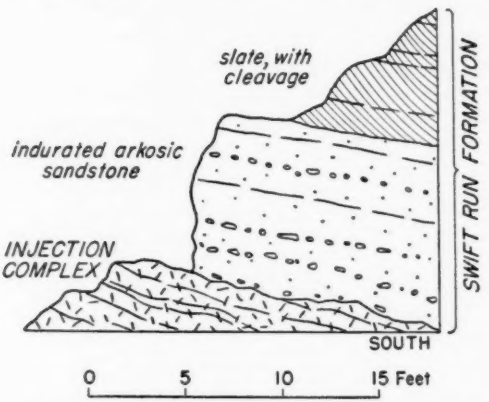


Figure 4. Sketch section of outcrop of Swift Run formation on south bank of East Branch of Naked Creek a mile east of Jollett, Page County, Virginia, showing relations with injection complex.

from Purcell Knob, northern Virginia, northward across the Potomac into Maryland. It was observed by the writer in the Shenandoah salient, in the northeast part of the Elkton area (fig. 5). It was observed farther southwest in Virginia by Knechtel (1943, pl. 29) in the Lyndhurst-Vesuvius area (fig. 1), and by Bloomer and Bloomer (1947, pp. 95-97) in the Buena Vista quadrangle. All the localities cited are along the

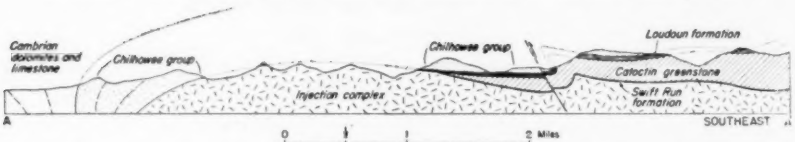


Figure 5. Geologic section across Shenandoah salient, Page County, Virginia, northeast of Elkton, showing relations of injection complex, Swift Run formation, and Catoctin greenstone to Chilhowee group. Based on observations by the writer.

northwest edge of the Blue Ridge; in the Blue Ridge itself the Catoctin is a thick and continuous body. The observed wedging out of the group is therefore probably not a set of unrelated local features, but represents a regional boundary

along which the Chilhoweee extended northwest across the edge of the Catoctin.

Bloomer and Bloomer (1947, pp. 104-105) interpret the passage from Catoctin to Chilhowee time as marked by a shift in the position of the basins of deposition, but believe that the relations are essentially conformable. However, in the Buena Vista quadrangle, the Catoctin greenstone and Oronoco formation are not in contact with the Chilhowee group, and occur in a different fault block, so the critical wedge relations at their edge cannot be observed. In the Shenandoah salient of the Elkton area, the wedge relations can be observed, and the Catoctin and Swift Run are definitely unconformable beneath the Chilhowee (fig. 5). Within the space of a few miles the Catoctin thins abruptly northwestward, the underlying Swift Run formation approaches the Chilhowee, and where the Catoctin is absent, lies directly beneath it. Still farther northwest, both the Catoctin and Swift Run are missing and the Chilhowee lies on the injection complex.

Erosion of the edges of the Catoctin greenstone before and during Chilhowee time is indicated by the common occurrence in the Weverton quartzite of jasper pebbles derived from amygdules in the lavas of the Catoctin (Keith, 1894, pp. 312-313). If the correlations within the Chilhowee group suggested earlier in this paper are correct, the unconformity between the Catoctin and the Chilhowee in northern Virginia would involve a hiatus of at least sufficient length to permit the deposition in northeast Tennessee of that part of the Unicoi older than the main volcanic zone.

The writer agrees with Bloomer and Bloomer that the change from Catoctin to Chilhowee time involved a shift in the position of the basin of deposition, but he believes that this also involved tilting of the edges of the older basin, erosion of the marginal beds of the basin, and probably a considerable time hiatus.

VOLCANICS OF MOUNT ROGERS AREA

Southwest of the James River on the northwest flank of the Blue Ridge, the Catoctin greenstone and underlying sedimentary rocks are absent, and the Chilhowee group lies for a distance of 120 miles on rocks of the injection complex (fig. 1). If any intervening sedimentary or volcanic rocks once existed,

they were removed by erosion prior to the deposition of the Chilhowee group.

In the vicinity of Mount Rogers, immediately north of the Virginia-Tennessee line, another body of volcanics lies beneath the Chilhowee group (Jonas and Stose, 1939, pp. 590-591). These volcanics are dominantly rhyolitic, whereas rhyolite is

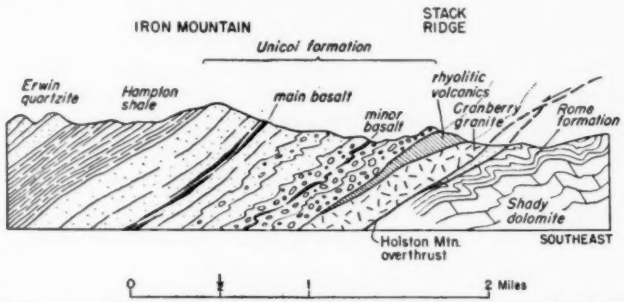


Figure 6. Geologic section through Iron Mountain and Stack Ridge, Johnson County, Tennessee, showing relations of Unicoi formation to rhyolitic volcanics and to Cranberry granite. The rhyolitic volcanics are a part of the volcanics of the Mount Rogers area. Based on observations of the writer and of H. W. Ferguson of the Tennessee Division of Geology.

subordinate in the area of the Catoctin greenstone, but they are considered to be the approximate equivalent of the Catoctin by Jonas and Stose (1939, p. 575). The volcanics of the Mount Rogers area are unconformable beneath the Chilhowee group, for "north of White Top these [volcanic] conglomerates dip under, and are parallel to, the Lower Cambrian, Unicoi formation, but at the only contact observed there was a slight angular unconformity between the two series. Eastward the beds of the volcanic series trend at an angle with the strike of the Unicoi formation and still farther east the volcanic series is not present and the Unicoi formation rests on the injection complex" (Jonas and Stose, 1939, p. 591).

The southwest edge of the volcanics of the Mount Rogers area extends across the Virginia-Tennessee line into Johnson County, northeast Tennessee, where relations similar to those just described have been observed by the writer and his colleagues (King and others, 1944, pp. 41-42, pl. 3). H. W. Ferguson has mapped rhyolitic lavas and indurated tuffs in the southeastern foothills of Iron Mountain—on Fodderstack Mountain and Stack Ridge (fig. 6). The volcanics are overlain

by conglomerates of the Unicoi formation which contain pebbles derived from the volcanics. On Stack Ridge the volcanics are a southwest tapering wedge between Cranberry granite below and Unicoi formation above. The wedge terminates at the southwest end of the ridge, and farther southwest in Tennessee the Unicoi lies directly on the Cranberry and other granites.

In the Mount Rogers area, as in northern Virginia, the volcanics are bodies of variable thickness lying beneath the Chilhowee group, which were apparently truncated by erosion before the beginning of Chilhowee time. As nearly 3,000 feet of the lower beds of the Unicoi intervene between the volcanics of Stack Ridge and the main volcanic zone of the Unicoi exposed on the slopes of Iron Mountain, it is evident that the two volcanic episodes are separated by a considerable time interval.

(*To Be Continued*)

THE FAULT AT THE WEST EDGE OF THE TRIASSIC IN SOUTHERN PENNSYLVANIA

GEORGE W. STOSE

ABSTRACT. The floor of the Triassic basin in southern Pennsylvania is exposed in several places close to the western margin of the basin where the thickest sediments would be expected. To explain this anomaly, a fault is postulated within the basin at the west edge of the deeper part. A line of stocks, representing magma that rose from a deep source, is believed to mark the line of the postulated fault.

IN southern Pennsylvania a longitudinal series of normal faults bounds the west edge of the Triassic, and is here referred to as the Triassic border fault. The Triassic sedimentary rocks, comprising arkosic sediments below—New Oxford formation—and the Gettysburg shale above, dip uniformly northwest at an average rate of about 30°. The Triassic formations were deposited in a basin which is believed (Stose, 1932, fig. 5, p. 54) to have progressively deepened westward, due to gradual sinking of the basin on a fault at the west margin, and the sedimentary layers overlapped each other westward. These Triassic formations have a combined aggregate thickness of about 23,000 feet in this area (Stose, 1929, pp. 8-10), and the greatest accumulation of sediments should occur at or near the west edge of the basin. Here the youngest beds of the Triassic are quartzose and limestone conglomerates derived from the waste of uplifted rocks northwest of the border fault (fig. 1). The presence of Paleozoic limestone forming the floor beneath these youngest Triassic rocks at and near the west edge of the basin in the Carlisle quadrangle (fig. 2), therefore, is not to be expected and requires explanation.

In the Carlisle quadrangle along the normal faults at the west edge of the Triassic, the youngest Triassic sedimentary beds in the down-dropped block comprise quartzose and limestone conglomerates, and the uplifted rocks to the west consist largely of late pre-Cambrian volcanic rocks. The Triassic conglomerates were formed from the waste of rocks then present west of the fault in the closing stages of Triassic deposition. The presence of quartzose conglomerate east of the fault indicates that the volcanic rocks northwest of the fault were still covered by Cambrian quartzite when the conglomerate accumulated. These quartzose conglomerates pass northward

into limestone conglomerate in the vicinity of Dillsburg, hence at the time of formation of this conglomerate Cambrian limestone capped the quartzite west of the bounding fault.

The limestone that forms the floor of the Triassic sediments east of the border fault (fig. 2) crops out in the valleys of South and West branches of Latimore Creek northwest of York Springs, and underlies the Triassic sedimentary rocks and an associated diabase flow or sill for a distance of 3 miles

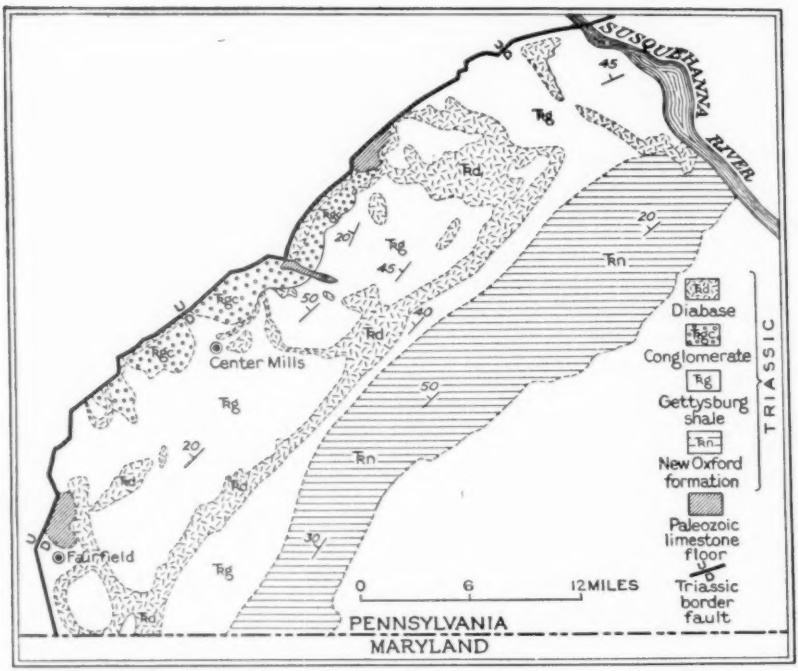


Fig. 1. Map of the Triassic rocks in southern Pennsylvania.

across the strike to the normal fault at the west border. The contact between the limestone floor and the overlying Triassic beds is approximately horizontal. Another area of the limestone floor beneath nearly horizontal Triassic limestone conglomerate and red sandstone in the Carlisle quadrangle is near the border fault in the lowland west of Dillsburg. A similar area of Paleozoic limestone east of the border fault forms the floor of Triassic conglomerate and sandstone just north of

Fairfield (fig. 1). These exposures of the limestone floor were at first explained (Stose and Lewis, 1916, p. 629) as due to the overlapping of Triassic sedimentary beds in a progressively westward sinking basin, but this interpretation was abandoned after detailed mapping of the area (Stose, 1929, p. 16).

Diabase intrusions in the Triassic sedimentary rocks consist of dikes, sills, large cross-cutting bodies, and stocks.

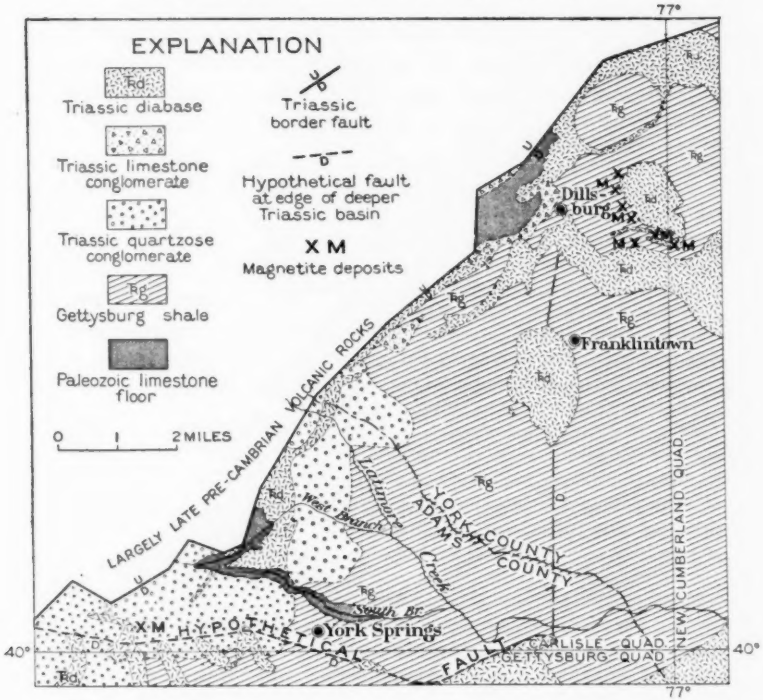


Fig. 2. Geologic map of part of the Carlisle quadrangle, Pa., and adjacent area.

Those who have studied these intrusive rocks and the associated magnetite deposits (Spencer, 1908, pp. 76-96; Harder, 1910, pp. 612-618; Smith, 1931, pp. 32-52) agree that the diabase originated in a deep-seated magmatic reservoir below the Triassic rocks, ascended through these rocks along vents, and are represented by stocks and large cross-cutting bodies. The large cross-cutting bodies (fig. 1) do not extend to the

west limit of the Triassic rocks but end east of the exposures of the limestone floor at Fairfield, York Springs, and Dillsburg. A large cross-cutting body east of the limestone floor exposed at Fairfield ends about 1 mile east of the border fault. The diabase bodies south of York Springs, along the south margin of the Carlisle quadrangle and the northern part of the Gettysburg quadrangle extending south to Central Mills, are cross-cutting bodies and are believed to represent a partially exposed large stock that lies south of the limestone floor at York Springs. The oval-shaped area of diabase at Franklintown appears to be a stock, and the large cross-cutting bodies southeast and east of Dillsburg are stocks that lie east of the limestone floor exposed in the vicinity of Dillsburg.

These cross-cutting bodies of diabase have a large content of original magnetite, which was a component of the deep-seated magma, and the occurrence of concentrated magnetite deposits in the metamorphosed rocks adjacent to most of these stocks, and deposits of garnet in the metamorphosed rocks, therefore, are believed to indicate that these stocks had direct connection with the deep source of the molten magma. It is suggested that the magma ascended from the deep source along faults in the floor of the Triassic basin at the west edge of a deeper part of the basin. Such a fault would extend to the bottom of the thick sediments accumulated in the basin, at a depth of about 20,000 feet, and deeper into the rocks of the floor beneath, and would provide a direct channel up which the magma could rise as it was squeezed out from beneath the sinking basis. This fault, which marks the west edge of the deeper basin, would be located at a line joining the northwest ends of the cross-cutting bodies and east of the limestone floor exposed at Dillsburg, York Springs, and Fairfield (fig. 2). Further evidence of the existence of such a fault is the fact that the Triassic beds to the east dip uniformly northwest, whereas those to the west are practically horizontal. The suggestion that such a fault might be present in the Triassic floor at the line of stocks representing vents from a deep source of the magma was proposed in the Adams County, Pa., report (Stose, 1932, fig. 5) and again in the York County, Pa., report (Stose and Jonas, 1939, pp. 118-119).

According to this hypothesis the thick deposits of Triassic

sediments, aggregating over 20,000 feet, would be limited to the deeper part of the basin east of the postulated fault. West of this fault the floor, composed of Paleozoic limestone, stood higher and received only the youngest Triassic sediments which overflowed the deeper basin (fig. 3). The overflow

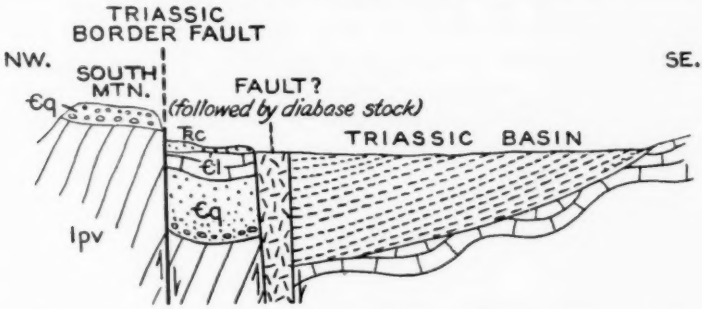


Fig. 3. Section across the Triassic basin, showing the western border fault, a postulated fault in the floor of the basin followed by a diabase stock, and the elevated floor west of this fault that received the overflow from the deeper Triassic basin to the east.

of the youngest Triasisc sediments onto the limestone floor northwest of the main basin was briefly referred to in the report on Carroll and Frederick Counties, Maryland (Stose and Stose, 1946, pp. 87-88). Movement on this fault must have ceased before the end of deposition and intrusion of diabase, as no evidence of faulting is observable in the sedimentary rocks now at the surface.

The explanation here offered accounts for the exposure of Paleozoic limestone as part of the floor beneath the youngest Triassic sedimentary rocks in the western part of the Carlisle quadrangle, where the greatest thickness of sedimentary rocks should normally occur. According to this interpretation, a fault, now covered or concealed, marked the west edge of the deeper part of the Triassic basin; this fault penetrated the floor of the basin to a depth of about 20,000 feet and tapped the source of deep-seated diabasic magmas; the diabase rose into the Triassic sedimentary rocks as cross-cutting bodies and stocks, and suplied the magnetite which has been concentrated in the metamorphosed sediments; a fault along the west edge of the Triassic was active at about the same time and Paleozoic limestone, which formerly capped the vol-

canic rocks west of this fault, was dropped to the level of York Springs and became the floor on which the youngest Triassic sediments were deposited as overflow from the main basin; later movement on the western fault raised the Cambrian quartzite and limestone west of the fault, and waste from their erosion became the conglomerates in the closing stages of deposition; erosion followed later uplift, and removed the Cambrian limestone and quartzite from the pre-Cambrian volcanic rocks now exposed west of the fault; still later movement on this fault has been postulated (Stose, 1927) to account for the displacement of the Schooley peneplain.

References

Harder, E. C., 1910. Structure and origin of the magnetite deposits near Dillsburg, York Co., Penna. Econ. Geology, **5**, 599-622.

Smith, L. I., 1931. Magnetite deposits of French Creek, Penna. Penna. Geol. Survey, 4th ser., M-**14**.

Spencer, A. C., 1908. Magnetite deposits of the Cornwall type in Berks and Lebanon Cos., Penna. U. S. Geol. Survey Bull. **359**.

Stose, A. J., and G. W., 1946. Geology of Carroll and Frederick Cos., Md. Md. Geol. Survey, Carroll and Frederick Cos., 11-131.

Stose, G. W., 1927. Possible post-Cretaceous faulting in the Appalachians. Geol. Soc. America Bull., **38**, 493-503.

———, 1929. U. S. Geol. Survey Geol. Atlas, Fairfield-Gettysburg folio (no. 225).

———, G. W., 1932. Geology and mineral resources of Adams Co., Penna. Penna. Geol. Survey, 4th ser., C-**1**.

———, and Jonas, A. I., 1939. Geology and mineral resources of York Co., Penna. Penna. Geol. Survey, 4th ser., C-**67**.

———, and Lewis, J. V., 1916. Triassic igneous rocks in the vicinity of Gettysburg, Penna. Geol. Soc. America Bull., **27**, 623-643.

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FABRIC CHANGES IN YULE MARBLE AFTER DEFORMATION IN COMPRESSION

ELEANORA BLISS KNOPF

PART II

Experimental Deformation of Yule Marble

After the fabric of the undeformed marble had been studied, test cylinders were cut from the marble so that in one set, known as the P cylinders, the cylinder axis is the north-south direction, i.e., the normal to the P face of the thin section block. (See fig. 1,b). In the second set, known as R cylinders, the cylinder axis is the vertical axis in nature, i.e., the normal to the R face of the thin section block. In the third set of cylinders, known as the Q cylinders, the cylinder axis is the east-west direction, i.e., the normal to the Q face of the thin section block. Each cylinder was marked with an arrow indicating a known direction normal to the cylinder axis, with the result that the cylinder is oriented with respect to the fabric coordinates determined by preliminary study.[25] The height of each cylinder is exactly one inch and the diameter of the cross section is one half inch. The accurate orientation of these cylinders and the careful turning and finishing required for test samples in high pressure deformation is an expensive operation. The cost of preparing the cylinders for deformation was covered by a grant-in-aid from the National Research Council, which is hereby acknowledged with deep thanks.

The technique of deformation is that described by Griggs in 1936[26] and the reader is referred to this paper for a description of the experimental work, as it has been impossible for Mr. Griggs to add a section on the technique on account of his full time diversion to war work during World War II, and

[25] Unfortunately in cutting the test cylinders it was not appreciated that *two* direction senses are required in order to establish the unique orientation of any thin section. Thus although the thin sections from the original thin section block of undeformed marble were cut with unique orientation, the thin sections from the deformed cylinders were cut with an ambiguity in the sense in two out of three recorded directions. This ambiguity was eliminated as far as possible by mutual comparison of all three sections for each cylinder and by recognition of residual lamellae maxima in the deformed fabric.

[26] Griggs, David T. Deformation of rocks under high confining pressures. Jour. Geology. **44**, 541-577. 1936.

his preoccupation with other responsibilities in the post-war period. In the course of preparation to resume experimental deformation in the Institute of Geophysics of the University of California at Los Angeles, Professor Griggs has very kindly furnished a considerable amount of data from his unpublished notes on work done in 1936 at the Physics Laboratory of Harvard University.

PROPOSED PLAN FOR EXPERIMENTAL DEFORMATION OF YULE MARBLE

The experimental deformation of the Yule marble cylinders was planned so as to apply compressional force to the dry marble upon each of the three faces, P, Q, R, of the thin section block under definite pressure-temperature conditions and also to the wet marble in the presence of carbonated water at temperatures that would favor the operation of recrystallization in the new fabric. It was also planned to apply a tensile stress to P, Q, R cylinders under similar conditions. Finally it was hoped: (1) that after cylinders deformed under conditions described above had been studied by petrofabric analysis it would be possible to deform a new set of cylinders whose axes would be inclined to the faces P, Q, R: (2) that deformation could be stopped at various stages of deformation, 5%, 10%, etc., and that the resultant change in fabric could then be determined during the progress of deformation.

The experimental work in compression and tension on P, Q, R cylinders was carried on in the Harvard Physics Laboratory by Griggs in cooperation with his assistant, James R. Balsley, Jr.[27] Four cylinders were deformed in compression: two P cylinders, one R, and one Q cylinder. Deformation was produced under three different pressure-temperature conditions: — 1. Dry deformation at 20° C. — two cylinders were used: one R cylinder, one Q cylinder; 2. Dry deformation at 150° C. — one P cylinder; 3. Deformation at 150° C in the presence of carbonated water — one P cylinder. Three cylinders, one P, one Q, and one R cylinder,

[27] This experimental work was supported jointly by the Committee on Geophysical Research and the Society of Fellows, Harvard University. The apparatus for the tension tests was constructed under Grant No. 201-37 made from the Penrose Research Fund of the Geological Society of America. For all this assistance sincere thanks are due.

were deformed in tension by Balsley. In the spring of 1941, he reported preliminary results of the deformation of the Yule marble in tension, at the meetings of the Tectonophysics Section of the American Geophysical Union.[28] As the experimental deformation was necessarily suspended during the duration of the war it has been impossible to carry out further stages of the work. It is hoped that the experimental work can be resumed in the near future and in the meantime Professor F. J. Turner of the University of California has made an exhaustive fabric study of more material from the Yule quarry, preparatory to further experimental work.

PROPOSED PLAN FOR PETROFABRIC ANALYSIS

After removal from the testing machine it was planned to cut thin sections from the surface normal to the cylinder axis and also from two mutually perpendicular surfaces parallel to the cylinder axis, in such a way that the three thin sections would correspond to the P, Q, and R faces of the original thin section block before deformation.

The following table shows the pressure-temperature conditions under which the P, Q, R cylinders were deformed in compression and the thin sections of the deformed cylinders that were studied petrographically and by petrofabric analyses.

DEFORMATION IN COMPRESSION

Experiment 70 — (R cylinder deformed dry at room temperature).

In this experiment the cylinder was cut so that the axis was normal to the R face of the thin-section block of undeformed marble and thus corresponds to the vertical axis in nature. Therefore the cylinder axis is approximately parallel to the *s* plane of the undeformed fabric (see fig. 1, a) and makes an angle of about 26° with the preferred orientation of the calcite optic axes.

The marble was jacketed in copper foil and deformed at room temperature (20°C) under a confining pressure of 10,000 atmospheres. Total deformation was about 36%, of which 16% was recovered on release of stress and removal

[28] Balsley, James R. Deformation of Marble under Tension at High Pressure. National Research Council Transactions, American Geophysical Union, Pt. 2, 519-525, 1941.

Experimental Work on Yule Marble in Compression

By D. T. Griggs, in the Physics Laboratory, Harvard University, 1936.

Cylinders cut with axis parallel to vertical axis in nature are R.
Cylinders cut with axis parallel to N-S axis in nature are P.
Cylinders cut with axis parallel to E-W axis in nature are Q.
Strength at atmospheric pressure = 4,220 lbs./sq. in.[29] (measured on R cylinder).

Exp.	Cylinder Axis	Confining Pressure in Atmospheres	Strain Meas'd Under Pressure	Recovery	Permanent Deformation	Change in Sp. Gr.	Symmetry of Deformation
70R	Vertical	10,000[30] t = 20°C	36%	16%	20%	—11%	Orthorhombic
73Q	E-W	10,000 t = 20°C	45%	20%	25%	—8%	Axial
74P	N-S	10,000 t = 150°C in the presence of carbonated water	39.3%[31]	(—1.3)%[31]	40.6%		Orthorhombic
75P	N-S	10,000 t = 150° dry	~30%[31]	(~2.4)%[31]	27.6%	—~9%	Orthorhombic

	Remarks
70R	Jacketed in Cu foil; load release instantaneous; elliptical cross section; ratio 1:1.20.
73Q	Jacketed in Cu foil; jacket broke; spec. broke on vertical N-S plane; circular cross section. Ellipticity 1.01.
74P	Jacketed in Cu foil; jacket broke; elliptical cross section; minor axis of ellipse parallel to dip; deforms by jerks.
75P	Jacketed in Cu foil; elliptical cross section; ratio 1:1.23; minor axis of ellipse parallel to the dip.

[29] For strength to rupture on variously oriented specimens see Lepper, Jr., H. A. Compression tests on oriented specimens of Yule marble, in this number of Am. Journal of Science.

[30] ± 10%.

[31] Apparatus not accurately calibrated at 150°C.

from the apparatus, so that the permanent deformation amounted to 20%.[32] As far as could be judged from the appearance of the test piece, deformation was homogeneous, with no measurable bulge. The cross section of the test piece became an ellipse having a ratio of 5:6 between the minor and major axes. The major axis lies in the east-west direction of the undeformed marble, thus indicating greater freedom of movement of material in the east-west than in the north-south direction, in other words, an orthorhombic rather than an axial strain.

Strength of the material at the maximum, when the experiment terminated, was more than 160,500 psi (see fig. 48) and the specific gravity was reduced 11%, measured after removal from the apparatus.

PETROFABRIC ANALYSIS

Thin sections were cut from the deformed test specimen as follows: one parallel to the end of the test pieces, which is parallel to the R face of the original thin section block; one parallel to the P face; and one parallel to the Q face of the original block. (See fig. 1,b). These sections were labelled 70R, 70P, and 70Q respectively. Photomicrographs of these thin sections are shown in plates 5, 6, 7.

A pronounced dimensional anisotropy in the grains can be recognized in the thin section, and is completely reoriented from the dimensional arrangement in the undeformed fabric. The P section shows a tendency towards grain elongation in the east-west direction; average grain size in the east-west direction is .75 mm. The Q section shows elongation in the north-south direction; average for the long diameter is .9 mm. In the R section the grains are more nearly equidimensional; average grain diameter .6 mm. This means that relatively flat grains are arranged with their flat sides in the horizontal plane, as contrasted to the undeformed fabric, in which the flat side of the grains occupies the north-south vertical plane. In the flat grains there are one or two sets of closely spaced lamellae. These lamellae are more numerous and more closely spaced than in the undeformed fabric and in many places are bent or twisted. Many grains are cloudy. They are more

[32] In this experiment owing to a failure in the upper piston, the confining pressure was released instantaneously without, however, causing any recognizable damage to the specimen.

conspicuous in the sections cut parallel to the axis of compressive force than in the section normal to the applied force.

Complete collective diagrams were prepared from the calcite lamellae and axes in the P, R, and Q sections. The same technique was used as in measuring the undeformed fabric. Grains numbered in the photomicrograph were measured and recorded, grain by grain. Measurements were plotted and contoured in elemental diagrams to test the homogeneity of the fabric in the thin section. The elemental diagrams show a marked similarity, which indicates an essential homogeneity of fabric, although there is a slight inhomogeneity between P and Q.

LAMELLAE DIAGRAMS

P Section: An elemental diagram from the P section (fig. 24) shows a marked concentration of lamellae poles lying close to the horizontal plane. A collective diagram made from 281 poles of calcite lamellae (fig. 25) shows the position of the main concentration of lamellae and indicates that this concentration is distributed into a maximum A and submaximum B, occupying two intersecting planes that make angles of 20° each with the horizontal plane. There is a stronger concentration of lamellae in the plane that dips 20° west (maximum A) than in the plane dipping 20° east (submaximum B), indicating an intensification of movement along one of the intersecting planes. A submaximum C about 25° from the east-west pole of the diagram occupying a plane that dips steeply east, probably represents a relic of the lamellae maxima of the undeformed fabric. The collective diagram of

In the following diagrams the one known direction sense in each thin section has been underlined.

Figure 24. 50 poles of calcite lamellae from P section of R cylinder after deformation. Contours 8-6-4-2-0%.

Figure 25. 281 poles of calcite lamellae from P section of R cylinder after deformation. Contours (7-5)-3-2-1-0%.

Figure 26. 320 poles of calcite lamellae from P section of R cylinder after deformation including 56 poles rotated from R to fill P. Contours (4-3)-2.5-2-1-0%.

Figure 27. 61 poles of calcite lamellae from R section of R cylinder after deformation. Contours (9-8)-6-4-3-2-0%.

Figure 28. 146 poles of calcite lamellae from R section of R cylinder after deformation. Contours (7-6)-4-3-2-1-0%.

Figure 29. 305 poles of calcite lamellae from R section of R cylinder after deformation: 150 poles measured in the R section, 155 poles rotated from P section. Contours (6-5)-4-3-2-1-0%.

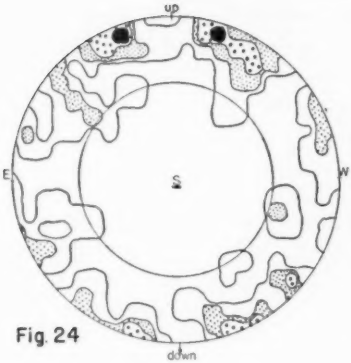

Fig. 24

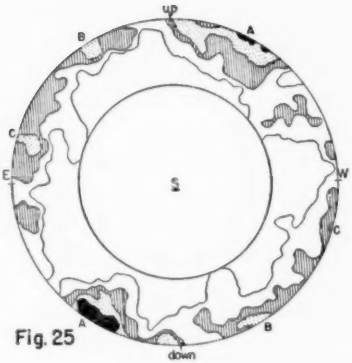

Fig. 25

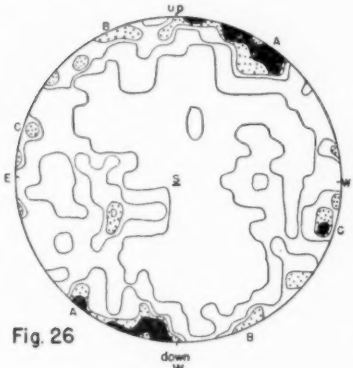

Fig. 26

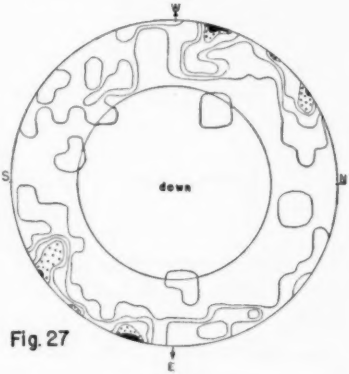

Fig. 27

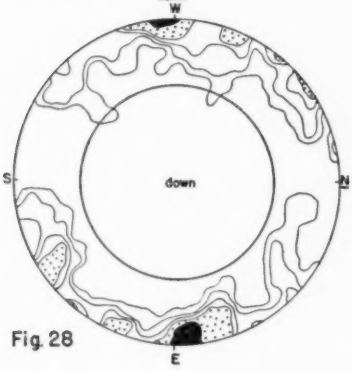

Fig. 28

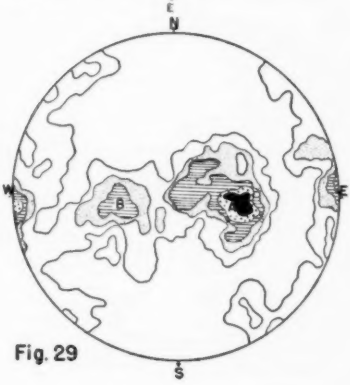

Fig. 29

P, filled from the R section, (fig. 26) indicates a minimum around the north-south direction and shows some concentration of lamellae (D) in the position occupied by the K maximum in the undeformed fabric. This submaximum at D probably is another relic of the lamellae maxima of the undeformed fabric.

R Section: An elemental diagram of 61 lamellae was contoured from the R section (fig. 27). Two other elemental diagrams of 50 and 40 lamellae respectively, established that the fabric is essentially homogeneous. Maxima are scattered and not very definite in position or outline, which is expectable because the predominant maxima from the P section lie close to the axis of compression and would therefore be unmeasurable in the R section. The maxima in R occupy the periphery of the diagram in a fairly wide arc on both sides of the emergence of the east-west axis. The most definite feature of the three elemental diagrams is the distinct minimum around the emergence of the north-south axis. The fabric as determined from figure 28, which is an unfilled collective diagram of 146 lamellae poles in R is not essentially unlike that in the undeformed marble (fig. 16), confirming the conclusion that this diagram represents a relic fabric. The new fabric associated with the new position of the megascopic slip plane that is indicated by the dimensional arrangement of the grains could only appear in diagrams measured from P or Q. In the *complete* collective diagram of R filled from P (fig. 29) it shows plainly.

Q Section: In the collective diagram measured from the Q section the lamellae are concentrated in a peripheral girdle

Figure 30. 380 poles of calcite lamellae from Q section of R cylinder after deformation: 257 poles measured in Q section, 123 poles rotated from P section. Contours $>$ 5-4-3-2-1-0%.

Figure 31. 80 poles of calcite lamellae from upper end of R cylinder after deformation; measured in Q section. Contours (12-10)-8-5-3-0%.

Figure 32. 63 poles of calcite lamellae from middle of R cylinder after deformation; measured in Q section. Contours (10-9)-8-6-4-3-0%.

Figure 33. 281 poles of calcite lamellae from P section of R cylinder after deformation; rotated to position of Q for comparison with Figure 30. Contours (7-5)-3-2-0%.

Figure 34. 53 optic axes of calcite from R section of R cylinder after deformation. Contours 8-6-4-0%.

Figure 35. 70 optic axes of calcite from Q section of R cylinder after deformation. Contours (10-8)-6-3-0-%.

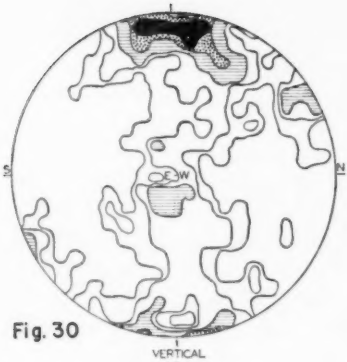

Fig. 30

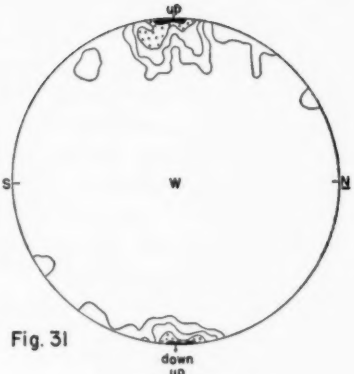

Fig. 31

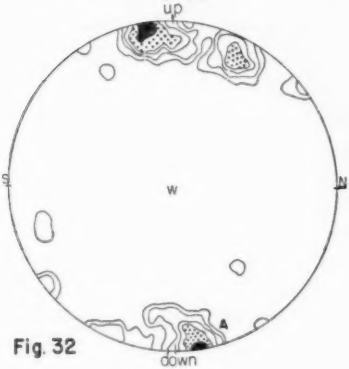

Fig. 32

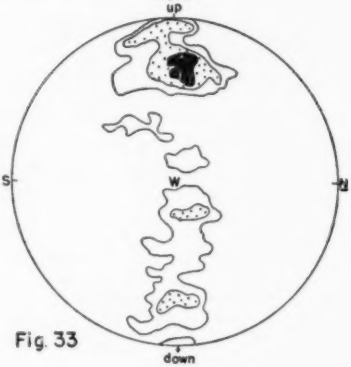

Fig. 33

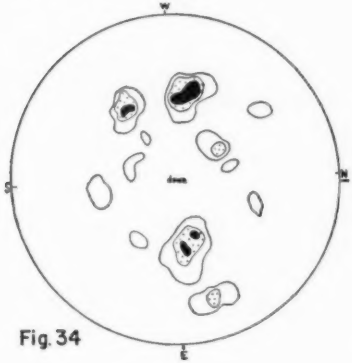

Fig. 34

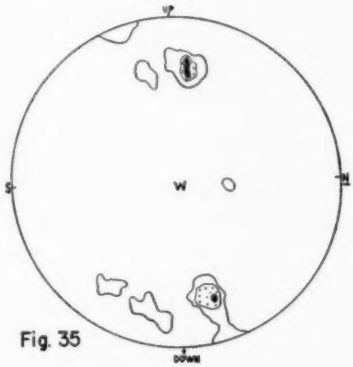

Fig. 35

with the maximum (fig. 30) close to the emergence of the vertical axis. There is a small angular divergence amounting to about 10° between the lamellae maximum and the vertical axis of the cylinder and the maximum is elongated in the E-W direction in the section measured from Q. In order to find out whether there is an essential difference between the course of the deformation at the end or in the middle of the cylinder a diagram was made from 80 lamellae at the upper end of the cylinder (fig. 31) and another from 63 lamellae from the middle of the cylinder (fig. 32). These two diagrams are essentially the same, showing that the deformation was penetrative and almost uniform in operation throughout the cylinder. In the complete collective diagram of 380 lamellae, 257 measured in Q and 123 rotated from P (fig. 30), the distance between the pole of the vertical cylinder axis and the lamellae maximum is considerably less in the Q than in the P section (fig. 25), so much so that even allowing for a possible divergence of a few degrees from 90° between the two sections due to inaccuracy of cut it may indicate a slight inhomogeneity in the fabric corresponding to the small rotation around the N-S axis of the original fabric. In order to test the degree of homogeneity in the fabric, the diagram of 281 lamellae measured in P (fig. 25) was rotated to the position of Q (fig. 33) to compare with the diagram of 380 lamellae in figure 30. The general correspondence of the pattern in the two diagrams outside of the blind area in Q is reasonably good.

AXES DIAGRAMS

Measurement of axes in these thin sections proved to be very unsatisfactory because: 1, the thin sections cut from the deformed cylinders are thicker than the standard thin section; 2, many calcite grains are twinned repeatedly, so that the twin lamellae are very closely spaced and do not allow the determination of axes; and 3, most grains are slightly biaxial, the axial angle being small and variable in amount.

It was possible to measure from the R section 53 axes (fig. 34), from the Q section 70 axes (fig. 35), and from the P section (fig. 36) 57 axes with an approximate degree of accuracy. The diagrams from the R and Q sections coincide reasonably well. In both diagrams two maxima lie on the vertical great

circle passing through the east-west direction. The maxima are about 35° distant from the axis of compressive force, which is, in this cylinder, the vertical direction.

In the R section the axes and lamellae maxima lie upon the vertical great circle passing through the east-west direction, thereby establishing the position of the deformation plane and the direction of movement as east-west, a conclusion that is confirmed by the maximum extension of the deformed cylinder in the east-west direction.

A slight tendency to elliptical arrangement of the axes in the R section coincides with the orientation of the elliptical cross section of the deformed cylinder and may suggest the influence of an elliptic conoid of shear, the major axis being in the east-west direction. However, this elliptical arrangement is not noticeable in the Q section, although the two axes maxima in the Q section lie upon the trace of this ellipse in Q.

In the P section one axis maximum lies so near to the position of the axes in the undeformed fabric that it probably represents a residual from the undeformed fabric. A maximum and a submaximum near the vertical poles probably represent changes of positions of axes during the course of deformation.

In order to estimate the relative frequency of various crystal planes among the measured lamellae, 118 lamellae were tabulated from the Q section of the deformed R cylinder. The tabulation showed: (1) the angles between the lamellae poles and the optic axes, (2) the angles between the lamellae poles in grains where more than one set of lamellae were measured. The following table shows the values for the crystallographic angles that occur most often.

Values of crystallographic angles in calcite

er	$(0001) \wedge (10\bar{1}1)$	=	44°36½′
ee	$(0001) \wedge (10\bar{1}2)$	=	**26°15′**
rr	$(10\bar{1}1) \wedge (\bar{1}101)$	=	74°55′
ee	$(01\bar{1}2) \wedge (\bar{1}012)$	=	45°3′
ef	$(0001) \wedge (02\bar{2}1)$	=	63°7′
em	$(0001) \wedge (10\bar{1}0)$	=	90°

Order of frequency of crystal planes among measured lamellae (in per cent of total grains measured)

Grains measured	Crystal plane	Frequency of occurrence
118	*e* $\{01\bar{1}2\}$	25%
	r $\{01\bar{1}1\}$	15%
	m $\{10\bar{1}0\}$	17%
	f $\{02\bar{2}1\}$	10%

However, it is impossible to measure enough optic axes with sufficient accuracy to justify any conclusion about the behavior of individual grains and the interpretations based upon the few measurements that were available can only be considered tentative unless confirmed by later work.

Experiment 75— (P cylinder deformed dry at 150°C.)

In this experiment the axis of the cylinder was cut parallel to the north-south axis in nature, i.e., normal to the P face of of the thin-section block in the undeformed marble. Therefore in this experiment as in 70 R the cylinder axis is nearly parallel to the plane of the grain (*s* plane) in the original fabric. (See fig. 1,a). The marble was jacketed as in Experiment 70 and deformed under a confining pressure of 10,000 atmospheres, the principal difference between the deformation of this cylinder and that of the R cylinder being that in this experiment the temperature was raised to 150° C. The permanent deformation in this experiment was 27.6%. As in Experiment 70 deformation was homogeneous, as far as could be determined from the external appearance of the test cylinder. The cross section of the test piece was again an ellipse with the major axis again oriented in the east-west direction.

PETROFABRIC ANALYSIS

Thin sections were cut from the P test cylinder just as in the R cylinder; one, parallel to the end of the cylinder is also parallel to the P section in the undeformed fabric; two other mutually perpendicular sections are parallel to the cylinder axis and to the R and Q section in the undeformed fabric (see fig. 1, b). Photomicrographs of these sections are shown in plates 8, 9, 10.

The three sections show the same dimensional anisotropy in the grains of the deformed marble, as seen in Experiment 70. In this cylinder, however, elongation is in the vertical direction in the Q section and in the E-W direction in the R section. In the P section the grains are more nearly equidimensional. In other words, the elongation represents a flattening in the directions normal to the axis of compression just as in Experiment 70. In the thin section the large grains are surrounded in some places by a border of smaller grains. The larger grains have clear-cut distinct outlines, forming a

mosaic. The traces of the lamellae in the deformed grains are much closer spaced and more abundant than in the fabric of the orginal Yule marble. In the Q and R sections almost every grain shows one or two sets of closely spaced lamellae. In the P section (normal to the compression axis) a number of grains are relatively free from lamellae.

The thin sections were studied in the same way as the thin sections of the R cylinder. Measurements were recorded, then plotted and contoured, first in elemental, then in collective diagrams, and finally the lamellae diagrams were filled by rotation.

LAMELLAE DIAGRAMS

Q Section: 280 lamellae were measured in 207 grains. These were contoured as 73 lamellae from 52 grains, 170 lamellae from 100 grains, and a final collective diagram of 280 lamellae from 207 grains. These diagrams were so consistently uniform, indicating such an essential homogeneity of the fabric, that only the final diagram (fig. 37) is published. The strong maximum A centers around the ends of the north-south pole in nature, which is the axis of compressive force in the experiment, and a moderately strong submaximum B occurs at about 24° below the N-S pole.

A diagram from 64 lamellae poles measured from the end of the cylinder is essentially homogeneous with a diagram made from 76 lamellae poles measured in the middle of the cylinder, thus showing, just as in Experiment 70, that the deformation was a homogeneous strain throughout the whole cylinder.

P Section: A diagram was made from 115 lamellae poles measured in the P section (fig. 38). This shows almost a complete peripheral girdle with a distinct minimum around the vertical direction in nature. The maxima that appear on either side of the east-west axis of the diagram are probably residual from the undeformed fabric.

The prominent maximum that appears in the Q section, which is the new arrangement induced by the deformation, could not of course appear in the unfilled diagram of P as it would occupy the blind spot.

R Section: A diagram of 63 lamellae, measured in the R section (fig. 39) shows an area of maximum concentration

about 35° west of north and another maximum about 15° west of north. These are clearly newly developed concentrations resulting from the compression in a north-south direction. There is a submaximum B in the northwest-southeast quadrant of the diagram at almost 80° from the dominant maxima at A. This submaximum appears with varying intensity in the elemental diagrams of 63 and 70 lamellae respectively, and probably represents a residual concentration from the original fabric before deformation.

The collective diagram of 135 lamellae (fig. 40), which corresponds perfectly to the elemental diagrams, shows the new maxima extending through an arc of about 50° west of north close to the axis of compression. This resembles so closely the arc of about 50° close to the axis of compression in Experiment 70 that it probably indicates the same flattening of grains in a plane normal to the axis of compression that is shown in Experiment 70. This same flattening of grains in the deformed P cylinder can be seen plainly in the photomicrographs of the R section (pl. 9) and of the Q section (pl. 10). The extension in the east-west direction shown in plate 9 is greater than in the vertical direction in plate 10. This greater east-west extension conforms to the east-west major axis of the elliptical cross section of the P cylinder.

The asymmetric position of the new maximum on the west side of the north-south axis in the R section shows a certain lack of homogeneity between the asymmetry in the R and in the Q sections that might be explained by a slight error of orientation in cutting the R section.

AXES DIAGRAMS

The same difficulty as in Experiment 70 was found in making accurate determination of optic axes orientation in Experi-

Figure 36. 57 optic axes of calcite from P section of R cylinder after deformation. Contours (12-10)-7-3-0%.

Figure 37. 280 poles of calcite lamellae from Q section of P cylinder after deformation. Contours (12-10)-8-6-4-2%.

Figure 38. 115 poles of calcite lamellae from P section of P cylinder after deformation. Contours (7-5)-4-3-2-0%

Figure 39. 63 poles of calcite lamellae from R section of P cylinder after deformation. Contours (10-7)-6-5-3-0%.

Figure 40. 135 poles of calcite lamellae in R section of P cylinder after deformation. Contours (7-5)-4-3-2-0%.

Figure 41. 62 optic axes of calcite from R section of P cylinder after deformation. Contours > 10-8-4-0%.

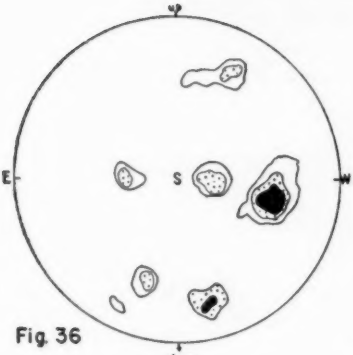

Fig. 36

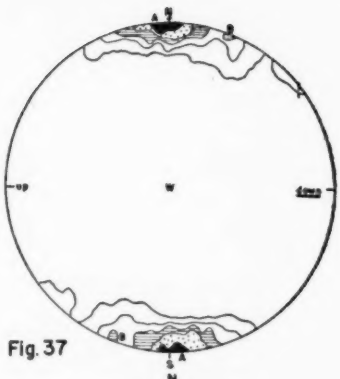

Fig. 37

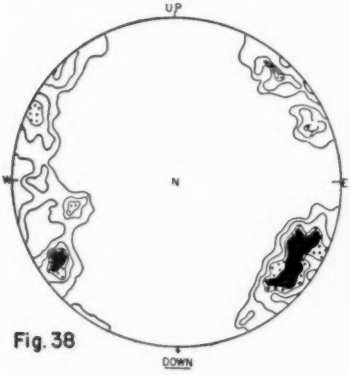

Fig. 38

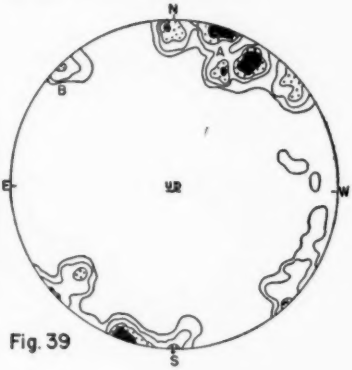

Fig. 39

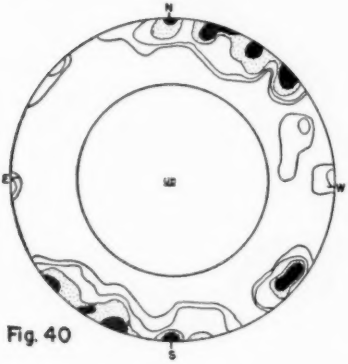

Fig. 40

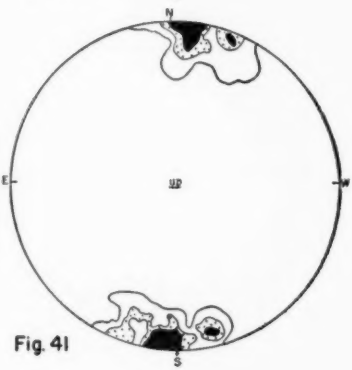

Fig. 41

ment 75. In the R section satisfactory measurements of 55 grains were obtained after checking each measurement three times. The significance of the pattern was established by the fact that its essential features were shown in a preliminary count of as few as 30 optic axes. The most that could be definitely established is that the optic axes in the R section of the P cylinder (fig. 41) are near the N-S direction in nature, thus near the lamellae pole maximum of the R section. This conclusion is justified by the general homogeneity of fabric indicated by the 62 optic axes measured in the R section (fig. 41) when compared with a collective diagram of 188 optic axes measured from the Q section (fig. 42). The same homogeneity of fabric was demonstrated by rotating the 62 axes measured in R (fig. 41) to the position of P for comparison with figure 43, which is a diagram of 163 axes in the P section of the P cylinder, measured independently at Harvard University in 1938.

The essential character of the diagram of 188 axes from the Q section (fig. 42) is clearly foreshadowed in elemental diagrams made from 52 axes, and 102 axes. In all these diagrams the two maxima are clustered at and near to the north-south direction, which is the axis of compression in the experiment.

This coincidence in pattern shows that the diagram in figure 42 is really a significant fabric pattern in spite of the difficulty in measuring optic axes in thick sections of strongly deformed calcite.

The biaxility of the calcite in P was examined in sodium light in thirty five grains. Of these about one half are clearly biaxial. Biaxial grains give no sharp extinction but show a

Figure 42. 188 optic axes of calcite from Q section of P cylinder after deformation. Contours (8-5)-4-3-2-0%.

Figure 43. 163 optic axes of calcite from P section of P cylinder. Contours $>$ 9-7-5-3-1-0%. (Diagram made by Snively and Bell.)

Figure 45. Cyclographic projection of a calcite crystal showing the areas where twin-gliding on one glide plane is impossible. Adapted from a diagram by James Forbes Bell.

Figure 46. Diagram showing areas in a calcite crystal where twin-gliding on {01$\bar{1}$2} under compression parallel to the optic axis is impossible. Adapted from a diagram by James F. Bell.

Figure 47. Diagram showing fields of permissible twin-gliding in undeformed Yule marble.

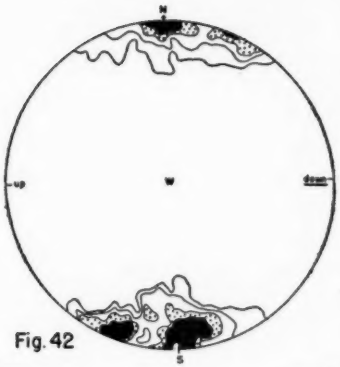

Fig. 42

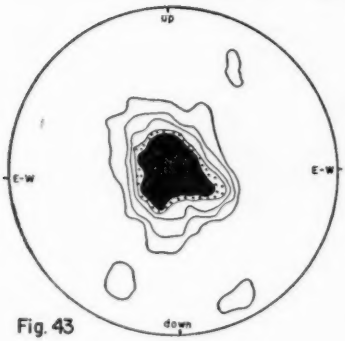

Fig. 43

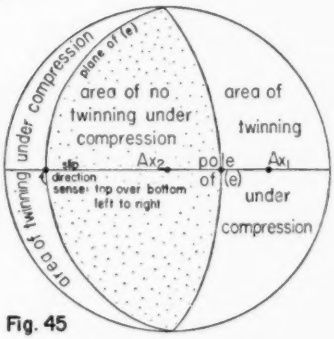

Fig. 45

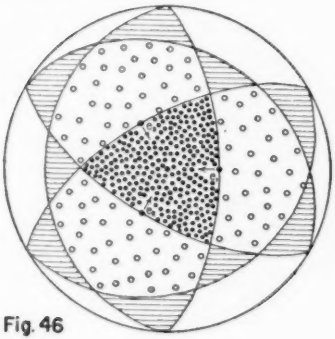

Fig. 46

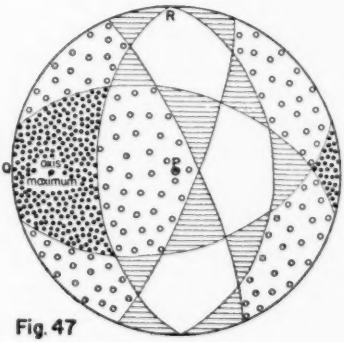

Fig. 47

blue mottling in the extinction position, a fact that has been noted by Gillson.[33]

Calcite grains in the P cylinder are much less murky than in the R cylinder and it is easier to get a good interference figure in sections normal to the cylinder axis than it is in sections normal to the axis of the R cylinder, therefore the biaxiality is more easily recognized in the P cylinder. In convergent light, fourteen out of eighteen biaxial grains in R showed a very small axial angle. No satisfactory estimate could be made for the percentage of biaxial grains in the R cylinder.

The relative frequency of occurrence of various crystal planes among the measured lamellae was examined in the same way as in Experiment 70 and the following table gives the results.

Order of frequency of crystal planes among measured lamellae (in percent of total grains measured)

Grains measured	Crystal plane	Frequency of occurrence
286	*e* {01$\bar{1}$2}	40%
	r {01$\bar{1}$1}	13%
	m {10$\bar{1}$0}	< 10%
	f {02$\bar{2}$1}	12%
	c {0001}	< 6%

The most striking difference between the deformed R and P cylinders is that the *e* plane is more strongly developed in the P cylinder. Also the basal plane appears to have functioned to a limited extent in the gliding process in P, whereas in the R cylinder there is no evidence of gliding on the base. It was pointed out by Eskola[34] that the structure of calcite can be considered as a distortion of the halite cubic structure. By this distortion the cubic planes would become the rhombohedral planes *r*. The plane that truncates the three rhombohedral edges in calcite is the basal plane. The plane that truncates three cubic edges in halite is the octohedron. It has been shown by Tammann and Salge[35] that above 100°C halite glides on (111) in a direction parallel to the edge [001:110]. It is interesting to note that in calcite the corresponding direction would be the direction in (0001) that is parallel to

[33] Gillson, J. L. Biaxial calcite. Am. Mineralogist, 12, 357, 1927.

[34] Eskola, P. Kristalle und Gesteine. p. 185. Springer Verlag. Wien 1946.

[35] Tammann, G. and Salge, W. Neues Jb. B. B. 57 A. 117, 1928.

the edge [01$\bar{1}$1:0001], which is the direction of alinement of nearest closest like ions, and therefore theoretically an expectable translation direction.[36]

Experiment 74 P — (P cylinder deformed at 150° C in carbonated water).

In this experiment the cylinder axis was parallel to the north-south direction in nature, normal to the P face of the thin-section block in the undeformed marble. The cylinder axis, as in 75 P, is nearly parallel to *s* in the original fabric.

The marble was jacketed in copper foil and deformed under a confining pressure of 10,000 atmospheres at 150°C in the presence of commercial carbonated water. Permanent deformation was 40.6%, the highest attained in any experiment. The deformation in this experiment took place by jerks. As in 70 R and 75 P the strain was orthorhombic and the deformed test piece again showed an elliptical cross section with the major axis of the ellipse in the east-west direction.

Extremely interesting is the texture of the deformed marble shown in the photomicrograph in plate 11. It is entirely different from the texture of cylinders that were deformed dry. The grains are clear, not turbid. Lamellae are sharp and straight with no sign of deformation and the texture is clearly that of a recrystallized fabric.

Unfortunately only one thin section was cut from this cylinder and study of this section has raised some doubt as to the correct orientation of the section. Therefore it has been impossible to draw any reliable conclusions about the deformed fabric. It is hoped that this extremely interesting experiment will be repeated soon and an exhaustive petrofabric study of the deformed material be made.

Experiment 73 Q — (Q cylinder deformed dry at room temperature).

In this experiment the axis of the cylinder was parallel to the east-west direction in nature, normal to the Q face of the thin-section block in the undeformed marble. Therefore the cylinder axis is normal to *s* in the undeformed fabric (see fig. 1,a) and makes an angle of about 26° with the optic axis maximum.

[36] Buerger, M. J. Translation-gliding in crystals. Am. Mineralogist, 15, 46, 1930.

The cylinder was jacketed in copper foil and the experiment was carried on at room temperature under 10,000 atmospheres confining pressure. During the run the jacket broke, permitting access of kerosene, and the specimen broke on the vertical plane striking north. Total deformation was 45%; recovery was 20%, leaving 25% permanent deformation. Reduction in specific gravity was 8%. The east-west extension attained in the other experiments was prohibited in this cylinder by the orientation and the deformation was an axial strain, producing a circular cross-section in the deformed cylinder.

Unfortunately no petrofabric analysis could be made, as the cylinder crumbled to powder before it could be sectioned.

RELATION OF DEFORMED TO UNDEFORMED FABRIC

The deformed fabric in the dry deformation of marble is characterized by the following features:

1. The change of grain shape from a position in the undeformed marble where the ellipsoidal grains are arranged with their shortest axis parallel to the east-west direction in nature to a position in the deformed fabric where the shortest axis of the ellipsoidal grains lies parallel to the axis of compression, regardless of whether the compressive force was applied parallel to the north-south or to the vertical direction in the undeformed fabric.

2. The lamellae in the deformed fabric are much more abundant and closer set than in the original fabric — they are frequently bent.

3. Biaxial character of calcite is more pronounced than in the original fabric.

4. The change in position of the ellipsoidal grains is accompanied by a general migration of lamellae maxima from positions close to east-west in the undeformed fabric to positions near the vertical in the deformed fabric of the R cylinder or near the N-S direction in the deformed fabric of the P cylinder, (fig. 1,b) i.e., to positions nearly normal to the axis of compression. This change is accompanied by a similar migration of optic axes from an almost horizontal position, a little north of west, to a position near the axis of compression. The shift in preferred orientation suggests

that the flattening of calcite grains in a plane normal to the compression has been accomplished by a mechanism of intragranular slip.

5. The symmetry of the deforming movement is not axial as might be expected from the operation of a cone of shear in isotropic material but is orthorhombic giving rise to the elliptical cross section of the deformed cylinder. The position of the major axis of this ellipse, i.e., the east-west direction, is predetermined by the relation of the optic axis maximum in the undeformed fabric to those lamellae maxima that make 26° angles with the optic axis maximum.

MECHANISM OF SLIP

It has been a matter of observation for many years that calcite can be made to change its optical orientation by twinning. Baumhauer[37] demonstrated this fact by pressing with a knife blade upon the edge [r:r]. The resultant crystal appears as in figure 44,a, which is slightly modified from a figure published by Denaeyer.[38]

The optic axis in the twinned portion of the crystal has moved through an angle of 52° from the original position. The movement was conducted along the glide plane *e* $(01\bar{1}2)$ in a direction that is fixed by the intersection between the glide plane and that plane normal to the glide plane which contains the optic axis of the untwinned portion of the crystal and the normal to the glide plane (fig. 44,b). This plane normal to the glide plane is the deformation plane of the twin-gliding movement.

It is obvious that a pressure P_2 in figure 44,a, applied upon the twin-gliding plane from the direction into which the twinned part of the crystal must move cannot produce twinning, because twin-gliding is a polar operation that can only be carried out in the direction sense required by the movement of the original optic axis through the pole of the glide plane into its new position.

Translation-gliding, which is a nonpolar movement, involving no change in optical orientation but merely a change in

[37] Baumhauer, H. Über künstliche Kalkspath-Zwillinge nach—1/2R—Zeitsch. Krist., 3, 588, 1879.

[38] Denaeyer, M. E. Caractères optiques des lamelles hémitropes b' $(01\bar{1}2)$ dans les clivages minces de la calcite. Soc. Géol. Belgique, **64**, Bull. 1, 2. 57-63, 1940.

shape similar to slip of cards in a card deck, can take place in a direction sense that is prohibited for twin-gliding. Thus although pressure applied in the direction P_2 cannot produce

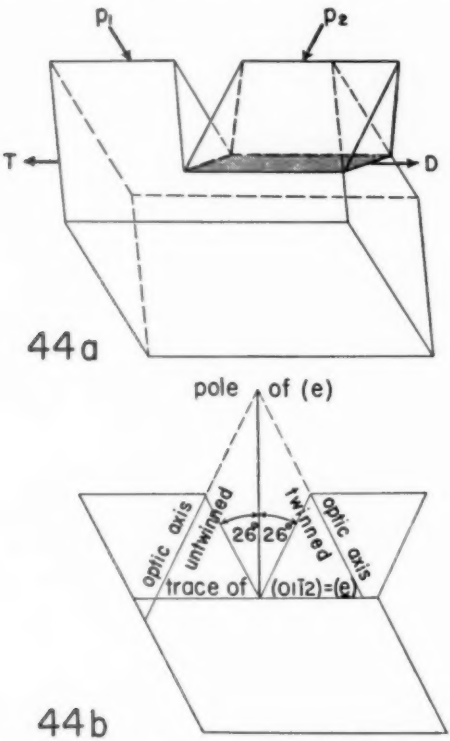

Figure 44. Diagram to show action of twin-gliding in calcite (not drawn to scale).

(a) Adapted from M. E. Denaeyer. Shaded plane is the glide plane (01$\bar{1}$2). D is the direction sense of the twin-gliding. The line joining DT is the direction of translation-gliding.

(b) Deformation plane of calcite twin. Position of optic axes is diagrammatic.

twin-gliding in the direction sense D it could produce translation-gliding in the direction sense T.

OPERATION OF SLIP THROUGH A DEFORMING MASS

Single crystals. It has been established for metal crystals in plastic deformation by twin-gliding or by translation-

gliding, that the slip movement starts on whichever potential gliding system the resolved shear stress is a maximum (Law of maximum resolved shear stress). A critical resolved shearing stress is necessary to initiate deformation. As a result of this slip a rotation of the slip system ensues, changing the stress field on the glide plane in such a way that a second glide system can function in crystals possessing more than one potential glide systems. When the resolved shear stress on the first glide system is equal to that in the second plane, double slip takes places in such a way that the movement proceeds down a symmetry plane between the two glide systems. When the change in shape brings the long axis of the deformed crystal into a plane that contains both glide directions, the reorientation ceases. In the course of deformation the operative glide systems change their positions with reference to the applied force. They tend to flatten out by tipping in towards the axis of tensile force or away from the axis of compression force. When the glide system is almost normal to the axis of compression, or almost parallel to the axis of tension (within 19° to 20°) the deformation ceases.

Polycrystalline aggregate. Conditions that govern individual grain gliding are complicated in polycrystalline material by various factors that do not enter into single crystal deformation. The influence of grain boundaries and the relative orientations of adjacent grains are two factors that constrain the flow of individual grains in an aggregate. This fact has been demonstrated by the contrast in behavior of hexagonal magnesium, with a single slip system, and face-centered cubic aluminum with its 12 equivalent glide systems. Polycrystalline magnesium is much stronger and less easily deformed than a single crystal of magnesium because of the resistance to movement offered by the diverse orientations of the one possible glide mechanism in the single crystal. In polycrystalline aluminum the resistance to deformation is much less than in magnesium because the 12 glide systems offer much more possibility for movement in individual grains.

However, even for metal working, which has been intensively studied in the last few decades, the understanding of the mechanism of flow in polycrystalline material is still far from satisfactory. It has been established by study of deformed material that polycrystalline metal develops, by working a definite and

characteristic "texture",[39] i.e., preferred orientation, just as in calcite marble deformation, calcite develops a characteristic preferred orientation pattern. How this reorientation of individual grains comes to pass is still a matter for study.

Two hypotheses that attempt to explain polycrystalline deformation on the basis of the mechanism of gliding in individual grains are:

1. Wever and W. E. Schmid's hypothesis of the actual rotation of the active translation plane around an axis that is normal to the direction of movement, — in petrofabric terms, a B axis of external rotation. Thus the ultimate position of the space lattice can be attained by the activation of two glide systems. This idea, however, fails to give a satisfactory explanation for the texture of face-centered metals deformed by rolling.

2. The explanation favored by Polanyi and other German metallographers, also by Taylor in Great Britain, was that the change in form in worked polycrystalline metal could be produced by the activation of three or, more easily of five crystallographically equivalent glide systems. Such a slip mechanism would develop a preferred orientation of glide systems normal to the axis of compressive force or parallel to the axis of tensile force.

So far very little is known about the actual mechanism of slip in polycrystalline monomineral aggregates of ionic crystals, or about the relation of twin-gliding to translation-gliding in plastic deformation of minerals.

An approach to this problem was made by Griggs,[40] who deformed clear crystals of Iceland spar free from cleavage flaws and visible twinning. Deformation was carried on at confining pressures ranging between 1 and 10,000 atmospheres. The cylinder was cut so that the long axis is parallel to one edge [r:r]. In this position two of the three potential *e* glide planes could function either by twin-gliding or translation-gliding. The third plane, being parallel to the direction of applied force, could not function. The two operative planes could conduct the extension of the crystal in a direc-

[39] "*Texture*" is used here in the sense of the metallographer, i.e. a preferred orientation pattern.

[40] Griggs, David T. Deformation of single calcite crystals under high confining pressures. Am. Mineralogist, **23**, 28-33, 1938.

tion that would be a compromise between the two twin-gliding directions in the two operative *e* planes. As pointed out by Griggs[41], fabric analysis proves the operation of twinning on these two planes. Moreover, the cross section of the deformed calcite cylinder is an elliptical section, just as in the deformed marble cylinders. By plotting on an equiareal net the position of operative glide directions in operative twin planes shown in thin sections of the calcite cylinder, it can be demonstrated that the compromise direction between these two positions coincides with the major axis of the elliptical cross section.

It is interesting to note the increase of ultimate strength that is produced in a single crystal of calcite by raising the confining pressure to 10,000 atmospheres. However the single crystal is weaker than the polycrystalline aggregate, i.e. it deforms to a greater extent than Yule marble does under identical confining and differential pressures. On the other hand, its deformability is much less than in the polycrystalline marble because at 10,000 atmospheres confining pressure the single calcite crystal ruptured after a 7% deformation whereas the polycrystalline Yule marble under the same conditions attained a permanent strain of 20%.

Griggs[42] has noted that pure translation, if present, was a minor factor in the deformation. Possibly the fact that polycrystalline marble deforms more than a single crystal of calcite before rupture is partly explicable by the combined influence of translation and twin-gliding in the polycrystalline aggregate.

When a calcite crystal is deformed by applying a compressive force parallel to the crystallographic *c* axis, the resolved shear stress would permit translation on all three glide systems but would not permit twinning, because movement in twinning would be opposed to the compressive force. It remains for future experimental work to demonstrate the relative strength of calcite crystals in various orientations.

RELATION OF TWIN-GLIDING TO TRANSLATION-GLIDING IN DEFORMATION OF YULE MARBLE

From the present study of deformed Yule marble it is clear that intragranular slip is responsible for much of the defor-

[41] Loc. cit. p. 31.

[42] Griggs, loc. cit., p. 33.

mation. The complete change of arrangement of the ellipsoidal or discoid grains between the undeformed and the deformed fabric has been accompanied by such a development of new and close-set lamellar structure that intragranular gliding must have operated to a marked extent, consequently the new fabric cannot be interpreted as wholly or largely caused by an intergranular rotation of the individual grains into a new position. Moreover, the demonstrable relation of the plane, determined by the pole of the lamellae maximum and the optic axes maximum in the undeformed fabric, to the elliptical cross section of the deformed cylinder proves the influence of intragranular slip in the deformation. The greater freedom of movement in the granular aggregate might be ascribed to the greater diversity of orientation of available glide planes in an aggregate as compared with a single crystal. Moreover it is possible that translation has operated to a considerable extent in the deformation of the marble whereas in the single crystal twinning was the most important mechanism of deformation.

It is difficult to evaluate the relative amount of translation-gliding and twin-gliding planes in the deformed fabric. In spite of the difficulty of measuring optic axes accurately in the relatively thick sections of deformed material it can be said with reasonable certainty that the majority of newly developed lamellae are the trace of *e* planes, which are known glide planes in calcite. But as calcite can glide on (*e*) by both translation and twinning this tells nothing about which process has operated. Where the individual bands of polysynthetic twins are broad enough to allow measurement of both optic axes the evidence of twinning is conclusive. Such measurable bands can rarely be found, however. Another clear evidence of twinning is the presence within the twin band of diagonal lamellae that make an angle with similar lamellae in the adjoining band. This also is rarely found. As pointed out by Buerger[43], a difference in extinction between two adjacent lamellae is not conclusive evidence of twinning because of the slight anisotropism likely to be caused by strain developed locally along glide planes. In many grains the color banding disappears when the lamellae are turned into a position where their bounding surfaces are parallel to the axis of the microscope. In thick sections this color-banding could

[43] Buerger, M. J. Translation-gliding in crystals. Am. Mineralogist, **15**, 57, 1930.

be a wedge effect caused by the diagonal position of the boundary surfaces of discontinuity. When these surfaces are placed upright their traces become hair-sharp lines and in polarized light the whole surface of the grain shows a uniform interference color. So many of the grains that were examined lacked conclusive evidence for twinning that probably translation has operated to a marked extent in deformation.

As twin-gliding can only proceed in one direction sense, the possible field of operation by twin-gliding for a given field of lamellae maxima can be computed, where the preferred orientation of the optic axes is also known, by means of a cyclographic[44] projection. Such a computation was prepared by Dr. James F. Bell on a Leitz stereographic net and was kindly furnished to the author. Figures 45 and 46 show adaptations on an equiareal net[45] of Dr. Bell's projection of glide plane and twin in a calcite crystal. It is easy to see from figure 45 that any pressure applied *against* the direction *into which* the calcite twin axis would move from the original untwinned position would prevent twinning in the area stippled in the figure. Pressure applied in the unstippled area would allow twinning.

In figure 46 the heavily stippled area represents the field in which twinning is impossible on all the three potential glide planes. In the areas occupied by the open circles twin-gliding could operate on one plane. In fields indicated by the horizontal ruling, twinning could function on two planes and in white areas twinning could function on all three planes. Translation could function on any of these planes, as it can operate in both senses of a direction.

Figure 47 was constructed by rotating figure 46, 64° from right to left to bring the optic axis of the single crystal into the position of the optic axes maximum in the fabric of the undeformed Yule marble. This brings the poles of (e_2) and (e_3) into the position of those lamellae in which the resolved shear stress on the glide systems would be great enough to allow gliding. The heavily stippled areas in this figure again represent fields in which compressive force would prohibit twin-gliding on all (e) planes. Twinning could operate to a limited degree in the areas occupied by open circles and horizontal

[44] A cyclographic projection is one in which the traces of planes are plotted as great circles.

[45] In this work the equiareal net has been used entirely in order to keep the results comparable although not entirely true in angular relation.

ruling, and could function on all potential glide planes in the white areas. Compressive force was applied to Yule marble in the positions shown by P, Q and R in the diagram.

The factor that controls the initial movement in plastic flow is the position of potential glide systems in the granular aggregate with reference to the direction of applied force. In figure 20 the dashed lines indicate the border of the field that would contain potential *e* glide planes related to the axes maxima in the Yule fabric. Plastic flow in the Q and R cylinders could start on *e* planes occupying any maximum except those in the east-west position, in which position the resolved shear stress would be zero for applied force that is either parallel or normal to the east-west direction, i.e., for Q, R, or P cylinders. In the P cylinder plastic flow could not start upon glide lamellae in any peripheral maxima because they are parallel to the P direction. However it could start on potential glide systems occupying other positions within the field of *e* planes related to the optic axis maximum. (See fig. 20).

A comparison of figure 20 with figure 47 indicates that when compressive force is applied in the Q direction the majority of glide lamellae are in the field where twinning would be a minimum. Pressure applied at R or at P, on the other hand, would be relatively favorable for twin-gliding.

The course of compressive deformation in R cylinders moves the lamellae maxima close to the R position in figure 47, i.e., closer to the field most favorable for twinning. In the P cylinder deformation moves the lamellae towards the position of P in figure 47. In this position the opportunity for twinning is much greater on one side of the east-west direction than it is on the other, a fact that may possibly be connected with the asymmetry of the lamellae shown in figures 37 and 40, which are diagrams of the P cylinder after deformation. The diagrams of the R cylinder after deformation are slightly asymmetrical but somewhat less so than the P cylinder diagrams. Further work on deformed cylinders will be necessary to establish the real significance of this asymmetry in the fabric.

Theoretically the operation of twin-gliding should be at a maximum in the deformation of the R and P cylinders. By the same reasoning compression of the Q cylinder would be least favorable for twin-gliding because the pressure is applied

in a field unfavorable for twinning and because the end position of the glide lamellae would be in the heavily stippled area in figure 47 where twinning is impossible. In the P cylinder twin-gliding should operate to a more limited extent than in the R cylinder.

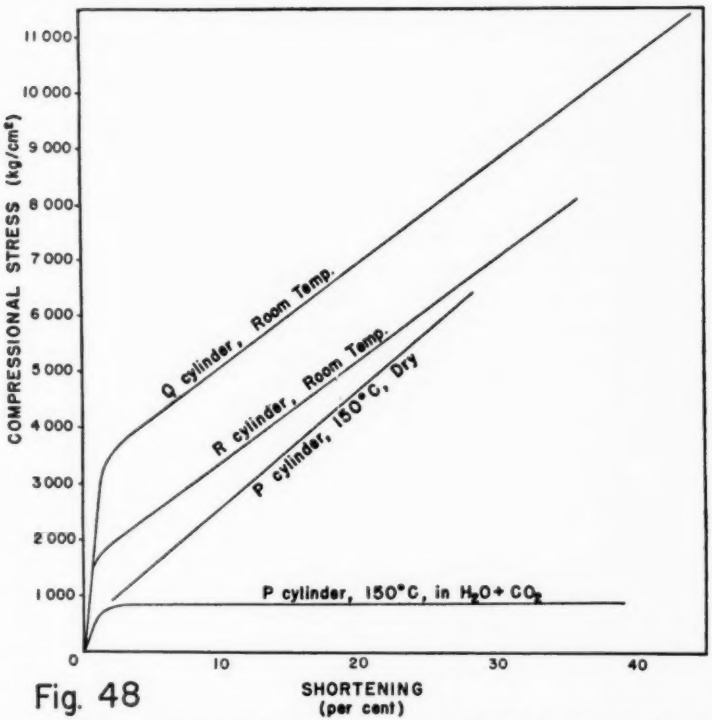

Fig. 48

Figure 48. Generalized stress-strain curves for Yule marble deformed in compression under 10,000 atmospheres confining pressure. Smoothed experimental data. (Courtesy of David T. Griggs.)

In this connection it is interesting to compare the strength of differently oriented cylinders. The difference in their reaction to compressive force is shown in figure 48, which shows the stress-strain curves for the deformation of P, Q, and R cylinders. This graph was kindly furnished by Professor Griggs, who emphasized the fact that the data from which he has constructed the curves, were unsatisfactory from the standpoint of physical measurement because they represent early experimental work before the apparatus and technique

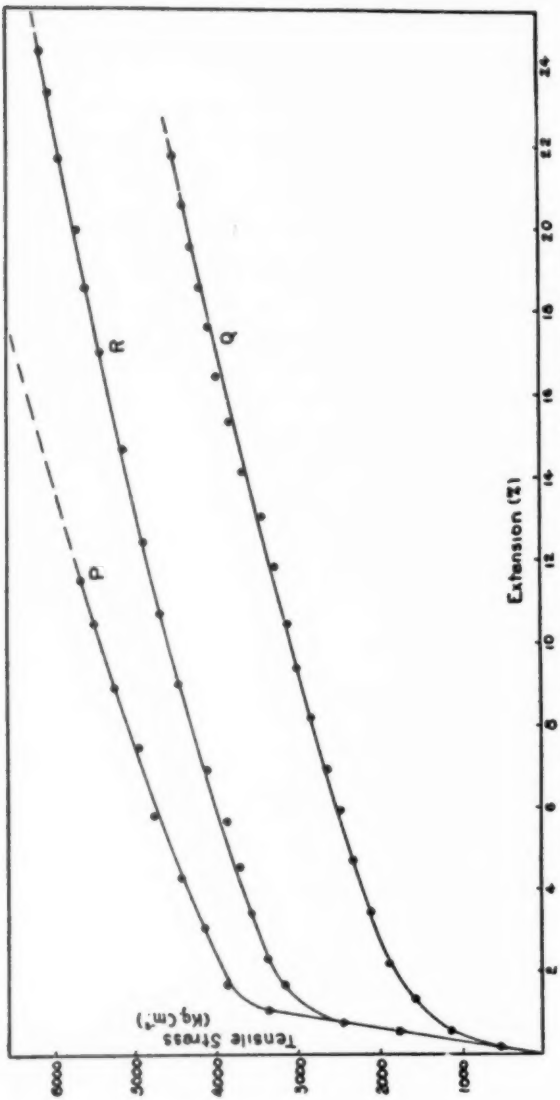

Figure 49. Stress-strain curves for Yule marble deformed in tension at 10,000 atmospheres confining pressure. (Balsley, J. R., Nat. Res. Council, Am. Geophysical Union, Transactions for 1941, p. 522.)

were perfected. He is hoping to run new compression tests with the most recent improvements in technique. The stress and strain determinations from which the generalized curves in figure 48 were plotted have been corrected as far as possible for change in shape of the cross section during compression, etc. and they probably represent what actually happened as well as can be reconstructed from the available data.

Comparison of these curves with Balsley's stress-strain curves in tension shown in figure 49 suggests a relation between the possibility of twin-gliding and strength in compression, similar to that suggested by Balsley[46] for deformation in tension. Positions favoring the operation of twin-gliding in tension are exactly reversed from the corresponding positions in compressive strain. Q is the cylinder that should expectably be the most favorably oriented for twin-gliding in tension and R and P should be the least favorable orientation for twinning, whereas in compression the Q cylinder is the least favorable and the R cylinder the most favorable for twinning.

In the following table strength of Yule marble in compression and in tension is compared.

	Deformation in compression				Deformation in tension		
	(measured in Kg/cm² at 10,000 atmospheres confining pressure)						
	Dry			in H_2O CO_2	Dry		
	20°C			150°C	20°C		
	Q	R	P	P	P	Q	R
Plastic yield point	3200	1500	~ 700	700	3400	~ 500	2500
10% strain	5100	3400	~2600	850	5400	3000	4600
20% strain	7000	5200	~4700	900	~6900	4200	5600
30% strain	8800	7000	~6800	900	....	....	....

From this table it is easy to see that strength in *compression* is a maximum in the Q cylinder where twin-gliding would be at a minimum and conversely it is a minimum in *tension* in the Q cylinder where twin-gliding could be a maximum. This

[46] Balsley, Jr., J. R. Deformation of marble under tension at high pressure. Am. Geophys. Union Trans. Pt. II, 519-525, 1941.

suggests, as pointed out by Balsley, that twinning has played an important part in deformation. The low values for strength in compression in the two P cylinders as contrasted with the values for R and P cannot be compared because P was not deformed under conditions comparable to the deformation of Q and R. A rise in temperature definitely facilitates compressive strain in both dry and wet deformation. In the presence of carbonated water, where recrystallization takes place, deformation continues after the plastic yield point, even with no appreciable increase in differential stress.

So far it is impossible to make a reliable estimate of the relative importance of twin-gliding and translation-gliding. We know, as shown by Bell, that translation-gliding can function under conditions where twin-gliding is impossible, but the relative ease of compressive and tensile deformation in cylinders that are oriented so that twin-gliding is permissible suggests that translation is facilitated to a large but undeterminable extent by twin-gliding, which, wherever it can operate, adds to the ductility. The relative importance of these two mechanisms of slip cannot be determined from evidence at hand.

CONCLUSIONS

Theoretically the possibility of intragranular grain-gliding in a monomineral polycrystalline calcite aggregate would be governed by the law of maximum resolved shear stress. For the fabric of the Yule marble this would determine the position where gliding on the $\{01\bar{1}2\}$ glide system would commence as a result of compressive force applied parallel to the cylinder axis in the P, R and Q cylinders. In the R and Q cylinders all maxima shown in figure 20 except the east-west maximum would contain grains on whose glide systems the resolved shearing stress would be a maximum. The susceptibility to glide in the grains occupying the east-west maximum would be a minimum but here translation-gliding would gradually change the shape and position of the operating grains and could thereby bring glide lamellae from the position of the east-west maximum into a position with reference to the applied force where they could glide. In the P cylinder the resolved shearing stress on the peripheral maxima in figure 20 would be so small that the movement would start on grains outside these maxima. Gliding in grains within these maxima would then gradually come into play. The most that can be said as a

Plate 5. Thin section from R cylinder after deformation in compression (dry at 20°C.) x ca. 15. Section cut normal to the cylinder axis, which is the axis of compressive force. The east-west axis of the elliptical cross section of the deformed cylinder is vertical in the photograph.

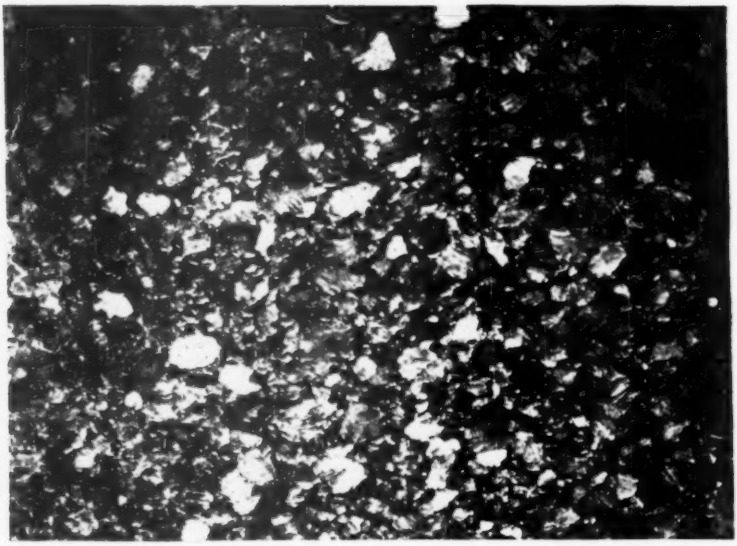

Plate 6. Thin section from R cylinder after compression (dry at 20°C.) x ca. 10. Section is parallel to P face of thin-section block, i.e. normal to north-south direction. The axis of compression was the vertical direction in the photograph. Note the elongation of the grains in a direction normal to the axis of compression.

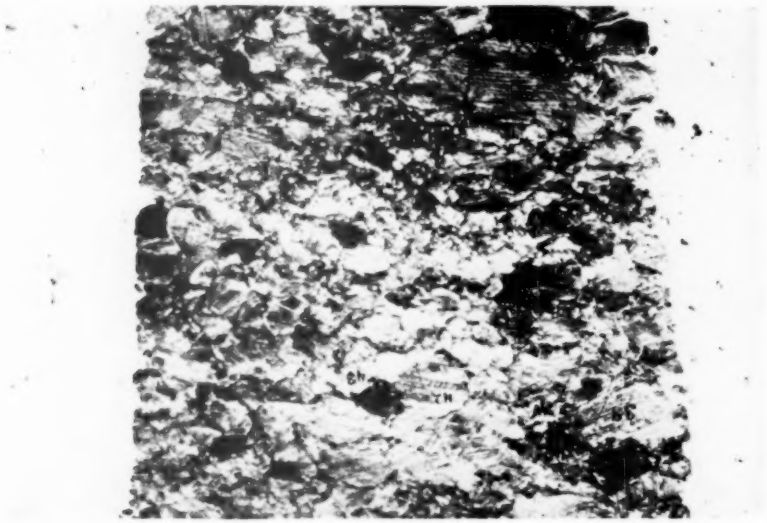

Plate 7. Thin section from R cylinder after compression (dry at 20°C.) x ca. 12. Section is parallel to Q face of thin-section block, i.e. normal to east-west direction. The axis of compression was the vertical direction in the photograph. Note the elongation of the grains in the direction normal to the axis of compression.

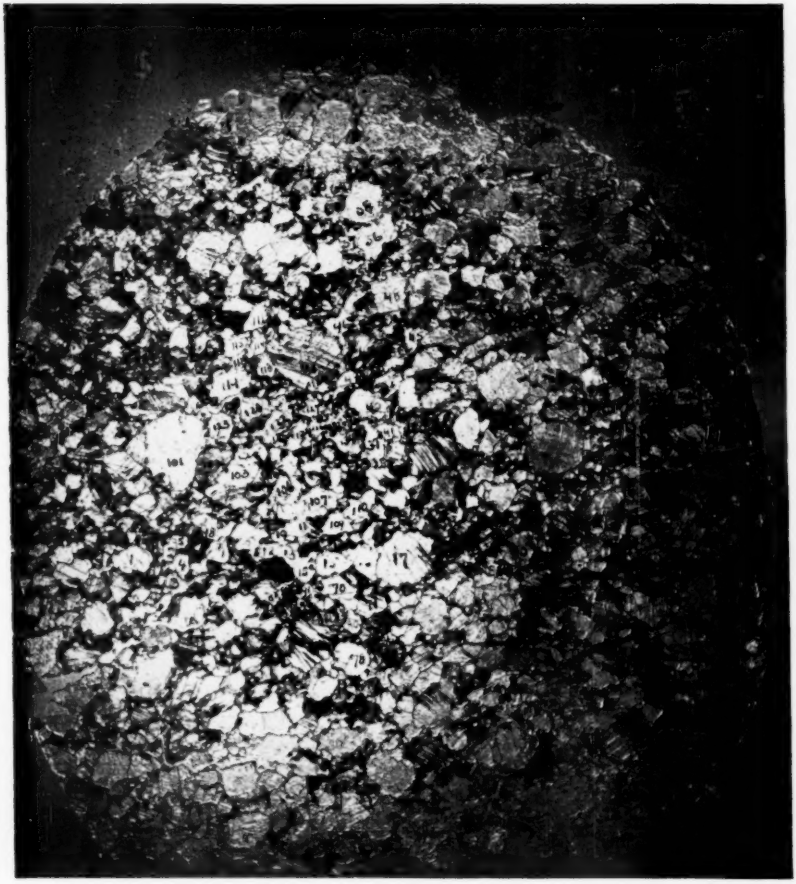

Plate 8. Thin secton from P cylinder after compression (dry at 150°C.) x ca. 15. Section is normal to the cylinder axis, which is the axis of compression. The east-west direction which is the major axis of elliptical cross section is vertical in the photograph.

Plate 9. Thin section from P cylinder after compression (dry at 150°C.) x ca. 15. Section is parallel to R face of thin-section block, i.e. normal to the vertical direction. Axis of compression was parallel to the vertical direction in the photograph. Note the elongation of the grains in the direction normal to the axis of compression.

Plate 10. Thin section from P cylinder after compression (dry at 150°C.) x ca. 20. Section is parallel to Q face of thin-section block, i.e. normal to the east-west direction. Axis of compression was parallel to the vertical direction in the photograph. Note the elongation of the grains in the direction normal to the axis of compression.

Plate 11. Thin section from P cylinder deformed in compression at 150°C, in carbonated water × ca. 45. Section is parallel to Q face of thin section block. Note the recrystallization fabric.

result of the present study of the deformed fabric is that the movement picture, indicated by the diagrams, shows clearly a rearrangement of the planar grain structure (*ab*) into a planar structure (a_2b_2) that is approximately normal to the compressive (see fig. 50). The twofold maximum that appears in the lamellae measurements in diagrams from both the R and

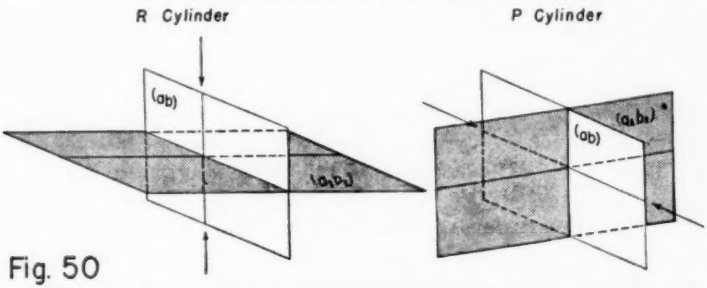

Fig. 50

Figure 50. Diagram showing rearrangement of planar structure in Yule marble as a result of deformation in compression. Arrows indicate direction of applied force. Unshaded planes show position of slip plane. (*ab*) in the unstrained fabric. Shaded planes show new positions of slip planes (a_2b_2) after strain.

the P cylinder is strongly suggestive of intragranular slip on two intersecting sets of slip planes, which is the "plättung" or flattening slip developed by the operation of two intersecting slip planes within the individual grains. This has been described by Sander[47] as a possible mechanism by which a foliation normal to the applied force is developed. In order to confirm this slip mechanism it will be necessary to measure, grain by grain, optic axes and lamellae so as to plot the crystallographic position of the lamellae and the positions of possible glide directions $[01\bar{1}2 : 0001]$, $[01\bar{1}1]$, $[01\bar{1}2]$. This will require thinner sections than were cut for the preliminary deformation work and such sections can doubtless be cut in future work.

The present study of fabric before and after deformation has established that a radical change in preferred orientation, both dimensional and crystallographic, has resulted from the deforming movement and that this change is definitely related to the fabric pattern of the undeformed marble. Beyond this, its chief value lies in pointing the way to individual problems of the deformation and to the way in which they may be attacked in future investigations.

[47] Sander, Bruno. Gefügekunde der Gesteine, 219-220, Wien, 1930.

COMPRESSION TESTS ON ORIENTED SPECIMENS OF YULE MARBLE

HENRY A. LEPPER, JR.

IN connection with her extensive studies of Yule marble, Mrs. Eleanora Bliss Knopf requested the writer to make compression strength tests on oriented samples of this material. Four test samples were prepared by Mrs. Knopf and were tested in the Materials Testing Laboratory, Department of Civil Engineering, Yale University, during the latter part of July, 1948.

Two pairs of specimens having known orientation with respect to the planar "grain" of the marble were prepared. The "grain" of the marble, recognized by the quarryman as the plane of easiest splitting, is a structure, determined by the dimensional arrangement of ellipsoidal calcite grains, oriented so that the shortest axis of the ellipsoid is normal to the grain. This dimensional arrangement is accompanied by a preferred orientation of the crystal lattice, determined by a statistical concentration of the calcite optic axes in a position that makes an angle of 26° with the "grain" structure.

The test specimens were prismatic, nominally one inch square cross-section and two inches long, with smooth finish on all surfaces. Specimens "A" were cut so that the compression force was applied parallel to the planar grain; in the other specimens "B" the force was applied normal to the grain. The direction of loading with respect to the grain and the location of the gages used to measure the strain in the direction of loading are shown on the sketches in figure 2.

Apparatus: A Southwark-Tate-Emery Universal Hydraulic Testing Machine of 120,000 lbs. capacity was used for the tests. The 12,000 lb. loading range of the machine was adequate for these specimens. This range could be read to 10 lbs. and has been calibrated to show an error of less than $\pm \frac{1}{2}$ per cent. In such a machine the specimen is subjected to a slowly increasing, steady strain while the load transmitted through the specimen as a result of the strain is indicated on the dial of the machine.

Strains were measured by "SR-4" resistance wire strain gages connected to a Baldwin-Southwark Portable Strain Indicator, Type K. These gages consist of a grid of fine wire

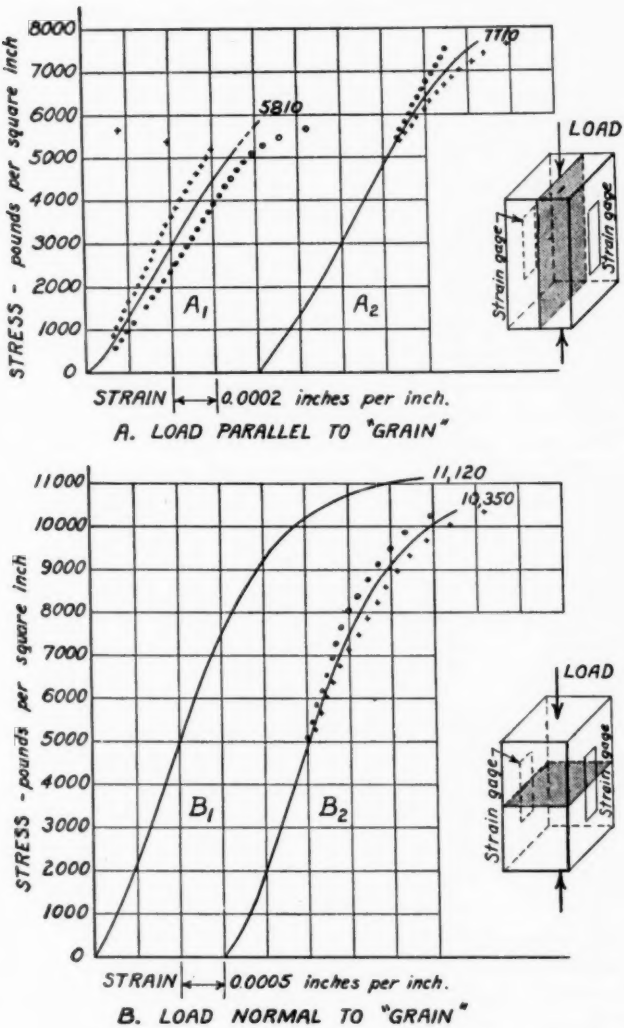

FIGURE 2. STRESS-STRAIN DIAGRAMS FOR YULE MARBLE TESTED IN COMPRESSION.

cemented to a paper back which in turn is cemented to the specimen. The cement bond is adequate to cause the wire to strain with the specimen, which strain produces a change in electrical resistance of the gage element. The strain indicator is essentially a bridge circuit for measuring this change in resistance and consequently the strain in the specimen.

Procedure: Each specimen was measured and strain gages were cemented in place at the centers of two opposite sides. Another gage to provide a balancing resistor for the indicator and temperature compensation in the strain readings was cemented to another piece of the marble which was placed on the testing machine near the test specimen.

Each specimen was mounted in the testing machine between solid bearing plates by seating the bearing faces in wet plaster of paris and then running the heads of the machine together until the excess plaster was squeezed out, leaving a thickness of 1/32 inch or less at each end. No appreciable load was required to do this. The plaster was allowed to harden overnight so that the specimen was firmly bedded in place for testing. This method of mounting the specimen was chosen to assure throughout the sample, uniform strain, which, if the material is statistically homogeneous, will provide uniform stress distribution on the cross-section. Better results are obtained this way than by the more commonly used spherical bearing block, with its attendant difficulties in accurate centering. A close-up view of the specimen placed in the machine is shown in figure 1. The felt pad covering one strain gage is seen on the side of the specimen, with the block for the compensating gage beside the test sample.

Loading during the test was continuous and at a practically constant rate of strain. Strain readings were taken at frequent load increments, each gage being read at alternate load points. Thus the loading could be kept steady and the two gages read and recorded. Maximum load was noted but because of the sudden failure it was not possible to measure the strains at this point. Following the test, each specimen was carefully removed from the machine to permit examination of the fracture.

Results: Complete stress-strain diagrams for the four tests are shown in figure 2. The plotted curves are based on the average of the two strain gage readings, with individual gage readings shown where there is appreciable divergence from the average curve.

The spread between the strains read on the two gages is a measure of the axiality of the loading. Agreement is quite good in all cases except specimen A_1, the first tested. In this case, the plaster used for bedding was probably not thoroughly hard, and the strains show appreciable differences. For specimen A_2 the strains agree well to a stress of about 6,000 lbs. per sq. inch, then show a divergence. This is believed to be due to nonhomogeneity in the material. Specimen B_1 shows excellent agreement to failure; B_2 is not so good but still satisfactory.

Strength results from these curves are summarized in Table I. Compressive strength is greater for loading normal to the plane of the "grain," but the stiffness of the marble (modulus of elasticity) is less than for loading parallel to "grain." The marble is capable of deforming about three times as far when loaded normal as when loaded parallel to grain. Thus the strength properties reflect the aelotropic nature of the marble.

TABLE I

Results of Compressive Tests

Specimen	Orientation	Compressive Strength lbs./in.²	Modulus of Elasticity lbs./in.²	Maximum Strain in./in.
A_1	Load parallel to grain	5,810	8,340,000	.0008
A_2	" " " "	7,710	9,000,000	.0010
B_1	Load normal to grain	11,120	5,420,000	.0038
B_2	" " " "	10,350	5,850,000	.0028

For a relatively brittle material, such as this marble, it is essential to secure uniform stress on the test specimen to give a correct value of compressive strength. If the test loading is eccentric, bending stresses will be introduced which produce a maximum stress appreciably greater than the average value calculated as the load divided by the cross-sectional area of the specimen. Failure occurs when this maximum stress reaches the strength of the material regardless of the value of average stress at the time. Such failure is progressive, starting at the high-stress region, and when a portion of the area has failed, the load must be supported by the remainder of the area, thus completing the failure. The maximum load then will be less than that required to bring the entire cross-section up to the compressive strength. The average stress

computed for this maximum load and reported as the ultimate strength will be appreciably less than the true ultimate strength.

Comparison of specimens A_1 and A_2 illustrate this point. A_2, with better loading conditions, showed 7,710 lbs. per sq. in. ultimate strength while A_1 gave only 5,810 lbs. per sq. in. The value for A_2 is felt to be a better result than A_1. The "B" specimens are in reasonably close agreement.

Specimen A_1 apparently had some kind of flaw in it which may have induced a premature failure. Evidence of this is seen in the readings of gage 2, which showed a decrease in strain after about 5,300 lbs. per sq. in. This was probably caused by a partial failure of the material which relieved a portion of the specimen of its stress. However, no further evidence of a flaw could be found upon visual examination. No unusual behavior was noted in any of the other tests.

Compressive strength of a material of this sort is affected by the proportions of the specimens and the end bearing conditions. The fully restrained ends of these tests will give higher strength results than if the specimens were of the same proportions but not so restrained at the bearing faces. Cube specimens would probably give higher strength, while a larger length-width ratio would give somewhat lower strength than these tests. Cylindrical specimens having a length-width ratio of two-to-one would probably show somewhat higher strength. In concrete, which is in some respects similar in its compressive properties to this marble, these effects have been studied in some detail.[1] These factors connected with the test itself illustrate the difficulty of determining the compressive strength of such material in a confined state or in large masses. Tests of the sort made here are chiefly useful for showing relative strength values and not absolute strength of a massive material.

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[1] Davis, H. E., Troxell, G. E., and Wiskocil, C. T., 1941. Testing and Inspection of Engineering Materials, McGraw-Hill, New York, pp. 102.

Figure 1. Close View of Specimen in Position for Test.

QUANTITATIVE AREAL GEOLOGY OF THE UNITED STATES

DONALD V. HIGGS

ABSTRACT. The areal exposure of each of the principal systems and series discriminated on the Geological Map of the United States (U. S. Geological Survey, 1933) has been determined from that map. Utilizing these data and the estimates of Holmes (1947) as to the durations of the corresponding periods and epochs, it is apparent that for each million years of geologic time the areal exposure of the corresponding rocks tends to diminish sharply with geologic age. This relation indicates that the probability of exposure of evidence for equivalent historical events likewise diminishes with geologic age. We can arrive at a crude quantitative estimate of the loss of record with time—a measure of "geological perspective."

INTRODUCTION

IN 1928 David White introduced a spiral graph "illustrating geologic time and the evolution of the earth's history." The object was to "present an appropriate, stimulating, and more adequate form of graph for use in developing the mental picture of the lapse of geologic time and superposed geologic history." The age determinations were approximately in accordance with the calculations of Holmes, Lawson, Schuchert and Barrell (White, 1928). More information is available now and, although the spiral graph is a striking representation, a somewhat different approach using more recent data may be worthwhile. This paper is based on quantitative data from the United States. By comparing areal exposure with duration of corresponding time units (as established by Holmes, 1947) we can estimate the probable completeness of the geologic record, and hence our chance of observing details of equivalent events in the different periods of geologic history.

Dr. James Gilluly, Professor of Geology at the University of California at Los Angeles, suggested the problem. His advice and criticisms are greatly appreciated.

PROCEDURE AND RESULTS

The area of exposure of each of the major units recognized on the Geological Map of the United States (U. S. Geological Survey, 1933) was determined by cutting up a map of the United States and weighing, separately, the paper pieces corresponding. The percentage of the total area of exposure within the continental limits of the United States then was computed for each of the units. The results are given in

table 1. Data for the major units (table 2) were obtained by combining the values of the smaller subdivisions. In the cases of undifferentiated units such as Quaternary-Pliocene sediments and extrusives, Pliocene-Miocene sediments and extrusives, et cetera, the values were divided equally among the periods or epochs concerned.

The estimates of areal exposure for the major divisions of geologic time are listed in table 2. These values were plotted on

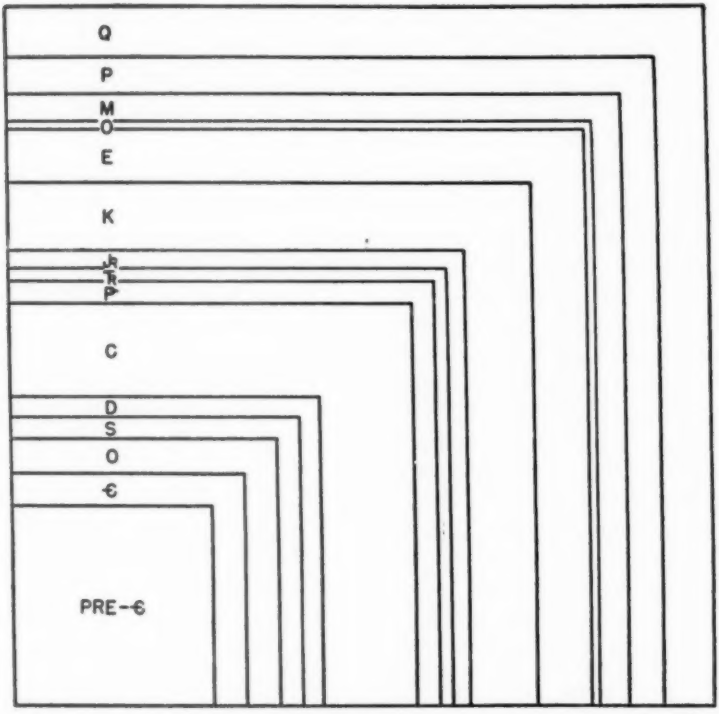

Figure 1. Cumulative graph representing areas of exposure of major rock units shown on Geologic Map of United States (column 1, table 2).

a graph, figure 1, to show the relative magnitudes of exposure. The values then were divided by the corresponding duration of time and the results (square miles/millions of years) were plotted as a factor graph, figure 2. Figure 3 is an isometric diagram representing the area of exposure plotted against time.

TABLE 1

Units Considered	Wgt. (gms.)	percent
Quaternary sediments	16.4682	12.43
Quaternary extrusives	.099	.074
Quaternary-Pliocene sediments	.580	.437
Quaternary-Pliocene extrusives	3.929	2.965
Pliocene sediments	3.985	3.007
Pliocene-Miocene sediments	5.619	4.241
Pliocene-Miocene extrusives	2.607	1.967
Miocene sediments	5.154	3.890
Oligocene sediments	1.128	.851
Eocene sediments	13.047	9.847
Eocene extrusives	.978	.738
Tertiary extrusives	3.477	2.624
Tertiary intrusives	.372	.280
U. Cretaceous sediments	14.853	11.232
L. Cretaceous sediments	.506	.381
Cretaceous sediments	3.053	2.326
Cretaceous-Jurassic sediments	.708	.534
Jurassic sediments	.803	.606
Jurassic intrusives	2.748	2.074
Jurassic-Triassic sediments	1.007	.760
Triassic sediments	1.673	1.262
Permian sediments	4.891	3.691
Pennsylvanian sediments	10.392	7.842
Mississippian sediments	5.643	4.250
Carboniferous sediments	1.075	.811
Carboniferous extrusives	.301	.227
Devonian sediments	3.353	2.530
Silurian sediments	3.003	2.266
Silurian-Ordovician sediments	.539	.406
Ordovician sediments	3.828	2.889
Ordovician rocks	.198	.149
Ordovician-Cambrian sediments	.305	.230
Cambrian sediments	2.385	1.800
Cambrian intrusives	.846	.638
Cambrian rocks	.236	.178
D-S-O-C sediments	.378	.285
Paleozoic undifferentiated	.429	.323
Paleozoic extrusives	.049	.036
Paleozoic intrusives	.602	.454
Pre-Cambrian sediments	5.491	4.144
Pre-Cambrian extrusives	.714	.538
Pre-Cambrian schist and ign. injec.	.536	.404
Pre-Cambrian sed. and ext.	.848	.640
ph — age unknown	.094	.070
Pre-Eocene sed. and ign. complex	.214	.161
Pre-Franciscan intrusive	.053	.040
	132.485	99.976

TABLE 2

	Area of exposure[1] in sq.miles	Percent of total exposure	Duration[2] (millions of years)	Area/millions of years
Quaternary	421,600	14.17	1	.421
Pliocene	254,000	8.54	11	.021
Miocene	229,600	7.72	14	.0164
Oligocene	47,000	1.58	12	.003917
Eocene	336,300	11.31	20	.01683
Cretaceous	442,600	14.21	69	.006120
Jurassic	99,080	3.33	25	.003961
Triassic	48,800	1.64	30	.001626
Permian	114,000	3.83	21	.005420
Carboniferous	395,300	13.28	52	.00760
Devonian	81,530	2.74	58	.001406
Silurian	79,800	2.68	37	.002150
Ordovician	106,300	3.57	80	.001328
Cambrian	87,510	2.94	80	.001094
Pre-Cambrian	250,800	8.43	2000±	.000125
TOTALS	2,974,220	99.97%		.509977

[1] Douglas, 1930.
[2] Holmes, 1947.

There are many errors inherent in this procedure, but in part they should be compensating. Errors involved in cutting the map are apparently no greater than the inaccuracies of the map. Variations in the weight of the paper are unavoidable and they are considered to be evenly distributed throughout the periods. The possibility that most of the heavier parts of the paper, for example, are included in the area of the Cretaceous exposures would be extremely fortuitous. Errors undoubtedly result from the arbitrary assignments made in those cases where rocks of several periods or epochs are not differentiated. Where this occurred the values were divided equally among the units involved. The values for the Tertiary igneous rocks, for example, were divided equally among the four epochs.

CONCLUSION

The factor graph (figure 2) depicts a measure of the relative clarity of the geologic record. The relative degrees of accuracy possible in detailed analysis of particular events occurring in different periods of geologic time can be determined. Thus the probability of correct interpretation of the Pleistocene glaciation is about 80 times greater than for Permian glaciation and about 3,500 times greater than for Pre-

Cambrian glaciation. Similar relations exist for other problems where specific processes have been noted as occurring in different periods of geologic time. This includes mountain building processes, igneous activities, geosynclinal sedimentation, conditions of aridity and many others.

Figure 3 illustrates the size of the source area from which the history of a given interval of time is to be derived. In the

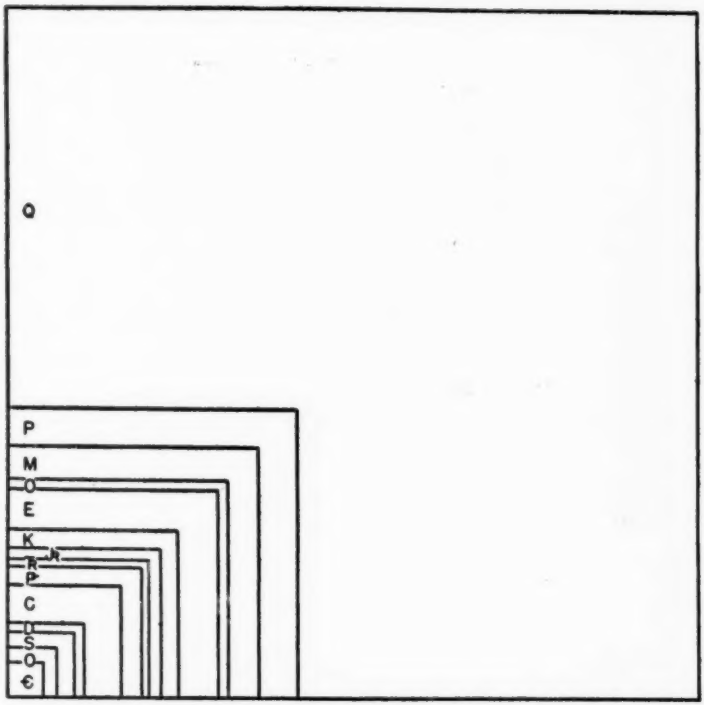

Figure 2. Cumulative factor graph showing relative clarity of the main units of the geologic record in area of exposure per million years of duration (column 4, table 2).

United States more than 75% of the earth's history (Pre-Cambrian) must be interpreted from less than 10% of the total area of exposure. Conversely about .05% of the record (Quaternary) is derived from 14.17% of the total area. Furthermore, rocks are altered by various processes after their formation and the older rocks generally are more changed. Therefore, the ratio of the areas of exposure presents the

maximum relative clarity and not the complete record. Hence, increasing clarity is directly proportional to decreasing time.

Since the geologic record rapidly becomes more obscure as the time factor is increased, it is impossible to determine the relative importance of particular events occurring at different periods in the earth's history. It would be hazardous to state,

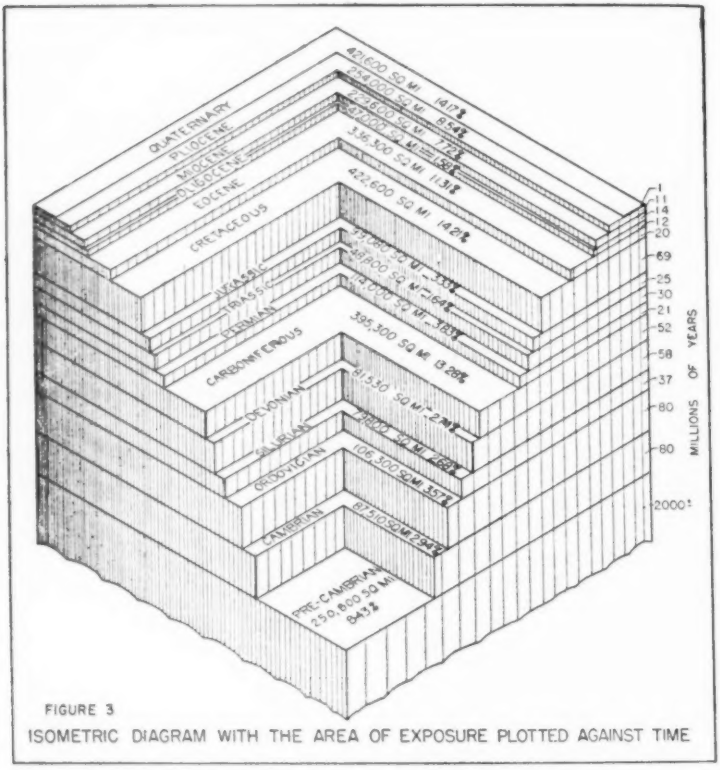

FIGURE 3
ISOMETRIC DIAGRAM WITH THE AREA OF EXPOSURE PLOTTED AGAINST TIME

Figure 3. Isometric diagram with the area of exposure plotted against time (columns 1 and 2, table 2).

for example, that orogenic movements during Pre-Cambrian time were of greater or less importance than orogenic movements during Tertiary time. A remarkably close correlation exists between curves representing thickness/time values and areal exposure/time values. The graphs, figures 4 and 5, were prepared by James Gilluly (1949), who very kindly permitted

their reproduction here. Figure 4 represents thickness per million years of the rocks corresponding to periods and epochs plotted against time since the middle of the period. The area of exposure for each million years of period length plotted against time since the middle of the period is shown in figure 5. Insufficient data prevent an accurate evaluation, but the trend

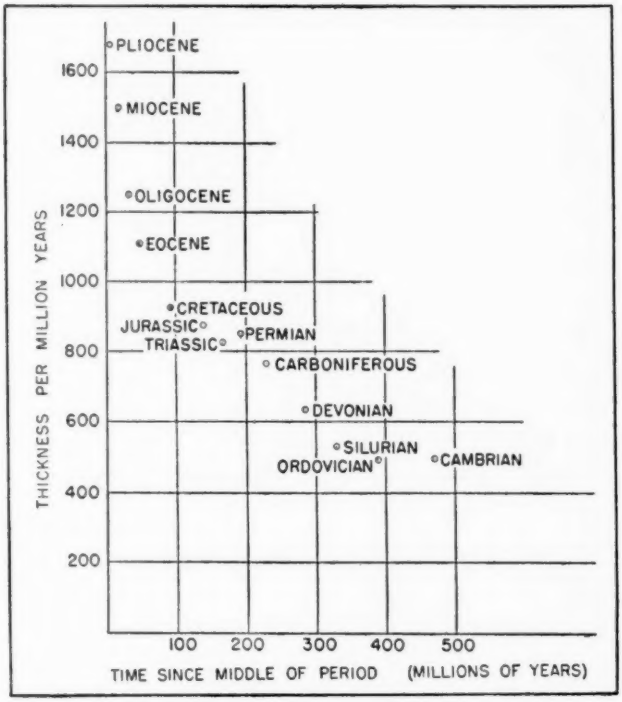

Figure 4. Thickness of rocks representing a period per million years plotted against time since middle of period (in millions of years). (Prepared by James Gilluly.)

of the curves is significant—constancy is the important implication. Deviations from the curve in figure 5 appear to be anomalous to the thesis. They may, however, be explained in part. Paleontologists are not in complete agreement as to the status of Oligocene. If it is grouped with the Eocene under the older term 'Eogene' epoch, the resulting value conforms to the general trend of the curve. Triassic and Jurassic

deflections probably would have been less if a larger, and more representative, unit of the earth's surface had been used.

The information presented is applicable, in the strictest sense, only to problems within the continental limits of the United States. Further work is planned to secure data from

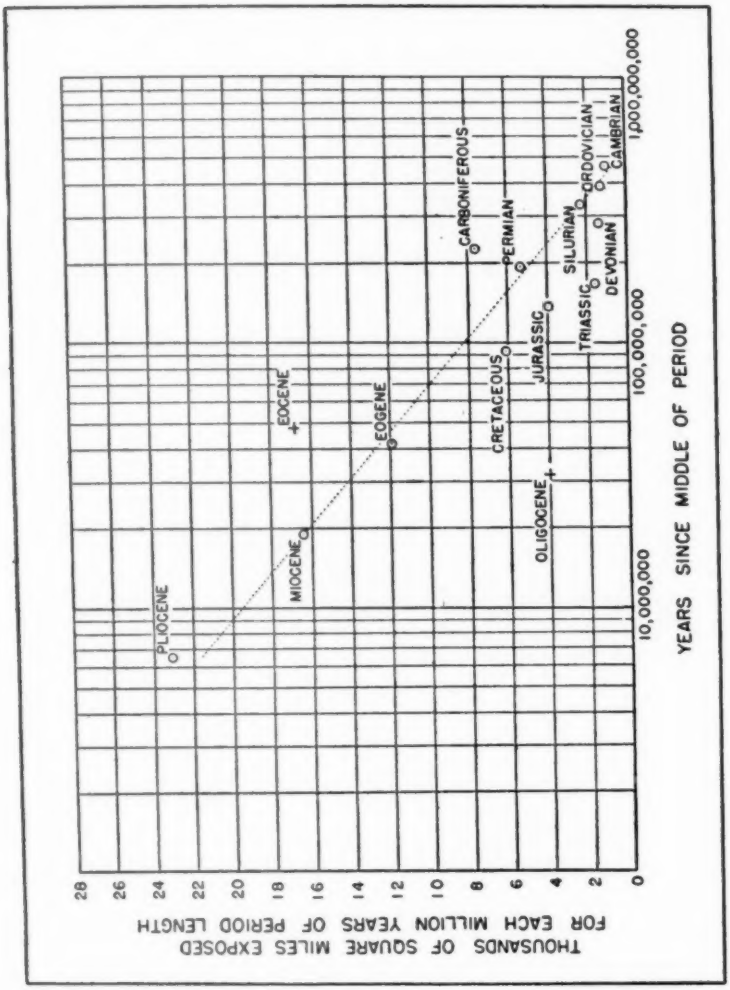

Figure 5. Thousands of square miles of exposure per million years of period length plotted against time since middle of period. (Prepared by James Gilluly.)

considerably larger portions of continental exposures. The relative values for such areas probably will be little changed, except that a curve corresponding to that of figure 5 may exhibit deflections of smaller magnitude. Perhaps the present time is not unique.

References

Douglas, E. M., 1930. Boundaries, Areas, Geographic Centers and Altitudes of the United States and the Several States. U. S. Geol. Survey Bull., **817**, 248.

Gilluly, James, 1949. The distribution of mountain building in geologic time. Bull. Geol. Soc. Am., **60**, no., no., 575-577.

Holmes, Arthur, 1947. The Construction of a Geological Time-Scale. Geology Soc. Glasgow Trans., **21**, part 1, 145.

White, David, 1928. A Spiral Graph of Geologic Time. Jour. Washington Acad. Sci., **18**, no. 8, 201-203.

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REVIEWS

The Atmospheres of the Earth and Planets; edited by GERARD P. KUIPER. Pp. vii, 366; 16 pls., 91 figs. Chicago, 1949 (University of Chicago Press, $7.50).—Telescopic observation has long proved inadequate to satisfy the general curiosity about the nature of the planets. Yet the physical analysis of their constitution has lagged behind the development of other branches of astronomy. As late as 1937 the Russian astrophysicist, B. P. Gerasimovič, the director of the great Poulkovo Observatory and former member of the Harvard faculty, lamented the neglect into which the study of the planets had fallen, while the exploration of the sidereal universe progressed rapidly. In particular, he urged the appreciation of the well-ripened methods of theoretical astrophysics to the analysis of planetary constitution. His own contribution, his last communication to reach the scientific world, was entitled "On the illumination of a planet covered with a thick atmosphere." The approximate solution given by Gerasimovič is superseded by recent work: Chandrasekhar has devised powerful mathematical methods capable of solving rigorously related problems of far greater complexity that only a few years ago would have seemed beyond hope of attack, like the distribution of polarization over the sunlit sky. Progress along the very lines Gerasimovič hoped for is admirably documented in the monograph under review. The editor is to be congratulated upon the organization of this symposium bringing together representatives of sciences usually regarded as far apart. Among the eighteen contributors are meteorologists, physicists, chemists, geologists and astronomers. Only some of the astronomical aspects will be commented upon here.

H. C. van de Hulst discusses "The scattering in the atmospheres of the earth and the planets," giving a comprehensive review of the physics of light scattering by particles of all sizes, based in part upon his recent Utrecht Thesis, which may be difficult to obtain in some places. This paper also contains a welcome summary of Chandrasekhar's solutions of problems of radiative transfer; Chandrasekhar's original publications are highly technical and treat only briefly of the physical background. Lyman Spitzer, Jr., deals with the rate of escape of gases from the gravitational field of a planet. Previous estimates of the time of escape must be increased by factors as large as 10^6 to allow for the fact that probably all the atmospheres are isothermal only at very great heights, with much lower temperatures in the stratospheres. Thus a temperature of 1500° K is required to disperse helium from the earth as fast as it is being liberated by denudation of rocks. Harrison Brown and the late Professor Rollin T. Chamberlin concur in the thesis that

the earth's atmosphere is almost entirely of secondary origin, and that it was evolved as the result of chemical processes that took place subsequent to the formation of the planet. This conclusion makes it the more important to establish spectroscopically the retention of hydrogen by the giant planets. A direct spectroscopic test is suggested by G. Herzberg's discovery in the laboratory of quadrupole lines of H_2 in the photographic infra-red; spectrograms of these lines are reproduced. With the apparatus here described absorption spectra over optical path-lengths up to 5500 m can be obtained. Th. Dunham, Jr., describes the spectographic studies of the planets carried out at Mt. Wilson over the last twenty years, which culminated in the discovery of CO_2 on Venus and the definitive identification of NH_3 and CH_4 in the spectra of the giant planets. During the past three years G. P. Kuiper has observed the infra-red spectra with a photoelectric cell of the Cashman type and achieved such spectacular results as the proof that Mars' atmosphere contains a small amount of CO_2, and that the reflection spectra of Saturn's rings and of Mars' polar caps closely resemble that of frost or ice. Kuiper's contribution also contains numerous quantitative data on the chemical composition of planetary atmospheres (partly derived in collaboration with Herzberg) and an approximate theory of the chemical processes by which the present-day composition of the atmospheres was brought about.

RUPERT WILDT

The Face of the Moon; by RALPH B. BALDWIN. Pp. xiv, 239; 17 pls., 26 figs. Chicago, 1949 (University of Chicago Press, $5.00).—The author of this lively book is an astronomer supporting by new evidence the thesis that impacts of meteorites were responsible for the remarkable surface features of the moon. He points out that a simple quadratic expression suffices to represent the relation between depth and diameter of such diverse objects as shell craters, bomb craters, explosion pits, terrestrial meteorite craters, and lunar craters. The good fit of this equation is indeed remarkable, considering a variation in size by a factor of 10^5 of the objects studied. There is an interesting survey of the problem of fossil terrestrial meteorite craters and a thorough discussion of the chance of observing telescopically the flash of light of a meteorite colliding with the moon, which the author deems remote. Most of the book deals with matters under jurisdiction of the geologist rather than of the astronomer. The astronomical data the author brings to bear upon the early history of the moon (chapter 10) are, perhaps, not quite as reliable as the author believes, and his conclusions as regards the time scale of lunar evolution should be accepted with reserve. The extensive bibliography does not con-

tain any references to modern attempts at explaining the lunar formations as result of orogenetic processes of the terrestrial kind. Conspicuous by absence also from other recent lists of reference is a memoir by Ingolf Ruud (Zeitschrift für Astrophysik 8, 295-343, 1934).

RUPERT WILDT

The Sphere of Sacrobosco and its Commentators: by LYNN THORNDIKE. Pp. x, 496. Chicago, 1949 (The University of Chicago Press, $10.00).—The Sphere of Johannes de Sacrobosco was used as an elementary manual of astronomy in the European Universities from the thirteenth until the seventeenth century. Its presentation of the elements of Ptolemaic astronomy has a lucidity that caused it to hold its place until the Copernican system was established.

A detailed introduction which contains abundant historical notes and details on manuscripts and early printed editions of the Sphere precedes the critical edition of the Latin text and its English translation. The remainder of the book contains various commentaries in Latin together with an English translation of the commentary of Robert Anglicus.

While the work is primarily of value to specialists in the field of the history of science and the history of scholasticism, it may be recommended to every teacher of elementary astronomy. Both the Sphere and the additional material presented serve as an excellent illustration of the astronomical thinking during the Middle Ages.

DIRK BROUWER

Abriss der Geologie (Emanuel Kayser) by PROF. DR. ROLAND BRINKMANN. Vol. 1, Allgemeine Geologie, 282 pages; vol. 2, Historische Geologie, 355 pages. Stuttgart, 1940 and 1948 (Ferdinand Enke. Vol. 1, 25 D.M., vol. 2, 17 D.M.).—This new edition—the sixth—of Kayser's "Abriss" has little in common with the older ones but the title and the general approach to the treatment of the subject matter. It is much less a text than a reference book. The student is not lectured to but presented with source material, charts, tables, and well chosen illustrations. As a source of information, the book is extremely valuable, especially on European data, as well as in philosophical outlook. Rich in literature references, it conveys an up-to-date picture of the status of geological work. Not competing with standard American texts, it will prove an extremely valuable and easily accessible source of information for advanced students and teachers of geology.

Volume 1—"general geology,"—is subdivided into exogenetic and endogenetic dynamics.

Solar energy keeps the exogenetic cycle in motion, thus air and water circulation, and climatic zones are discussed in the first part.

Physical and chemical weathering follow. Ground water and running water are accompanied by only a brief discussion of valley development, river systems, and sedimentation. Physiographic evolution, land forms, glaciation, weathering, soil formation, deserts, and wind action are discussed from the point of view of dominating climatic conditions.

Part 3 deals with shape and inorganic and organic content of oceans; and part 4 is devoted to oceanic regions, coastal zones, shelfs, and deep sea. The fifth part is a discussion of diagenesis and sedimentary rocks. The latter are listed in a systematic table together with equivalent mineral resources. This approach to exogenetic dynamics differs fundamentally from the viewpoint of standard American texts, and provides a continuous thread to the story.

Endogenetic dynamics comprises 4 parts: Tectonics, Magma, Regional Metamorphism, and Structure and movement picture of the globe in 12 chapters.

Tectonics deals with crustal movements, architecture, and structure. Earthquakes (seismometry and the earth's interior) are recent tectonics and may result in abnormal positions of bedded rocks.

Structural geology includes folding, jointing, morphology and structure, crustal movements, and regional distribution of structures. An example of statistical analyses using the equal area net shows the approach to detailed tectonic analysis but the general emphasis is on the regional distribution of tectonic types.

Architectural forms differ where magma is involved either near the surface (volcanism) or at depth (plutonism). The magmatic rock is the product of either. Mineral resources related to igneous phenomena conclude this part. Regional metamorphism is treated briefly but adequately with reference to the most important contributors and their work.

A general review of earth physics and geophysical methods concludes the first volume and deals with density, isostasy, geochemistry, geotectonics and geotectonic theories.

Volume 2—"historical geology"—opens with methods and results of geologic time-measurement. "Erdgeschichte" proper begins in the "Grundgebirge" or basement complex, whose distribution and subdivision are briefly outlined.

From the Cambrian to the Quaternary, 10 chapters describe the geologic column systematically. Each chapter contains introductory material, a discussion of the distribution of formations over the whole world, their paleontological content, climatic conditions, facies, crustal movements, short summary, and literature references. A large correlation chart accompanies each chapter and permits comparison on a world-wide basis. Palaeogeographic maps illustrate

local distribution as well as world-wide correlations. A large amount of information is concentrated into each chapter.

The systematic part is followed by two summarizing chapters on evolution—with an easily comprehended chart (p. 310)—and on the earth's history.

This volume is also more a source than a text. It contains no especially attractive titles and no catching story, but includes the basic facts in a systematic and easily available form. It may well prove to be the most useful key to European stratigraphy.

The second volume appeared in 1948 and thus the paper is not equal to that in the first volume (1940), but all illustrations are very good, and the printing is up to the best tradition of the publisher.

Author and publisher can be congratulated upon completion of this work under the most adverse conditions imaginable.

ERNST CLOOS

Introduction to Atomic Physics; by OTTO OLDENBERG. Pp. xiii, 373. New York, 1949 (McGraw Hill, $5.00).—This book describes the elements of atomic physics to students who have taken a one year introductory physics course. The arrangement of subject matter is somewhat unusual and gives evidence of the author's concern for the difficulties of teaching the subject to beginners. The treatment conveys not merely a knowledge of the facts of atomic physics, but an understanding for the intimate connection between experiment and theory. From the point of view of integration the book is one of the best I have seen. It is recommended strongly to anyone who wishes a balanced view of modern physics. The author is to be congratulated on his skillful use of historical and methodological material. H. MARGENAU

Foundations of Modern Physics; by THOMAS B. BROWN. Pp. xvi. 391. New York, 1949. Second Edition of a book first published in 1940 (John Wiley and Sons, $5.00).—Like Oldenberg's, this book covers the realm of modern atomic physics. It is essentially a serial description of experimental facts, simply presented and easily placed within the grasp of the beginner. It is less successful, in this reviewer's opinion, in integrating the conceptual and experimental components of modern physics than the book described in the preceding review. H. MARGENAU

The Science and Engineering of Nuclear Power. Vol. II; CLARK GOODMAN, Editor. Pp. 317. Cambridge, Mass., 1949 (Addison-Wesley Press, $7.50).—The first volume with this title was reviewed in the March 1948 issue of this JOURNAL. None of the remarks made by the present writer in that review about the trans-

cending importance of our newly gained knowledge of how to release in a controlled manner and on a large scale the energy stored in the nuclei of atoms need be repeated. Like the earlier book, this volume is based upon a series of seminars held at the Massachusetts Institute of Technology. It is interesting to observe how much can be told about nuclear reactors despite security regulations.

Whereas Volume I was primarily a general survey of the fundamental scientific facts about nuclear chain reactors, the contributors to Volume II write on specific aspects in some detail. Pile theory is discussed by F. L. Friedman, A. M. Weinberg, G. Placzek, H. Soodak and F. de Hoffman. With respect to nuclear engineering, there are chapters on heat removal from nuclear reactors, rockets and other thermal jets using nuclear energy, the shielding of nuclear reactors, effects of radiation on materials, and pile materials (metals, alloys and compounds). There is a valuable chapter on the production of "radionuclides" (radioactive atoms) by J. W. Irvine, Jr., and another on "health physics—instrumentation and hazard evaluation" by R. D. Evans. The book concludes with an interesting chapter by the editor on future developments in nuclear energy.

An appendix giving surveys of the unclassified literature on the energy release of the fission process, the electromagnetic methods of separating isotopes, and the number of secondary neutrons per fission should be very useful. A Segré chart summarizing the principal properties of the known atomic nuclei is also included.

It is obvious that just about all that can be written today about the physics of nuclear chain reactions and the engineering problems connected with the peace-time development of nuclear power is included in these two volumes. The discussions are authoritative and designed for the well-trained scientist. These books are a great contribution to the needed dissemination of the facts about nuclear energy.

W. W. WATSON

Botanik der Gegenwart und Vorzeit in culturhistorischer Entwickelung. Ein Beitrag zur Geschichte der abendländischen Völker. Von Karl F. W. Jessen, 1864 (Pallas, Vol. 1) Pp. xxii, 495. (Waltham, Mass.: Chronica Botanica Co.; New York City: Stechert-Hafner, Inc., 1948, $6.00).—Histories inevitably do more than provide chronicles of the events of which they treat, for they reflect the main stream of ideas and beliefs of the periods in which they were written. The spectacular success of the great "History of Botany" by Julius Sachs, published in 1875, was not entirely due to the fact that it came from the pen of one of the outstanding botanists then active. Its lucid, dynamically critical, and eminently personal style, applied to botanical development during its later, richest phases, fell

into line remarkably well with that "heroic" spirit in nineteenth century science which for many signified the commencement of a new era, an age enlightened and dominated by science and reason. The work of Sachs naturally overshadowed the somewhat earlier treatises of his contemporaries, such as Ernst Meyer and Karl F. W. Jessen.

Our thanks are due . . Frans Verdoorn (Chronica Botanica Company) for the excellent offset reprint edition (in German) of Jessen's rare original book which was published in 1864. This volume, printed on fine paper, is the first in a series of re-issues of classical biological works. The book should be of interest and value to both professional historians of the natural sciences and medicine and to other biologists with historical and humanistic leanings. In many respects Jessen's book supplements that of Sachs.

The history by Sachs begins with the early sixteenth century while a large portion of Jessen's book (the first ten chapters) is devoted to the beginnings of botanical science among the ancients and during the Middle Ages. Against the background of general cultural, religious, and scientific development, Jessen traces the gradual changes in botanical knowledge among the early Indians, Egyptians, and Babylonians, the Greek and the Romans, and during the early Christian era in Eastern and Western Europe. The contributions of Arabic science to botany are followed by a discussion of the beginnings of scientific activity in relation to cultural centers and schools in Western Europe. This leads approximately up to the period where Sachs begins. In the ten chapters which follow are notable sections dealing with the development of systematic botany from the early beginning to Endlicher as well as with that of agriculture and horticulture; the concluding sections discuss the general progress in natural and botanical sciences during the eighteenth and nineteenth centuries. Three appended tables illustrate the development of systematic botany, the number of botanical works printed, and notable botanical exploratory travels.

The book supplies much factual information in a field not easily accessible to most; many data and names are included, yet this does not interfere with pleasant reading. Thus in several respects the book is more than a history of botany. Its historical, philosophical, and cultural digressions demonstrate to the present reader the state of general humanistic knowledge which a scientist was able and inclined to acquire and put to good use one hundred years ago. In contemporary college teaching of botany, with its increasing accent on the role of plants in civilizations, Jessen's work should be of considerable value.

ROBERT BLOCH

The Avian Egg; *by* ALEXIS L. ROMANOFF and ANASTASIA J. ROMANOFF. Pp. 918; 424 figs. New York, 1949 (John Wiley & Sons, $14.00).—The authors of this work, recognizing that their title has almost universal symbolic connotations, use a brief preface to define their subject as 'an attempt to compile all the facts known about the bird's egg' . . . Further: 'We have limited our discussion to the egg before activation of life within it.' Thus in the controversy as to whether the hen precedes the egg or vice versa, their position is squarely for the former view: the egg as end-product. As is stated farther on (p. 175), 'Through the centuries, classical works have described in detail the development of the embryo within the hen's egg, but little attention has been given to the process by which the egg itself is formed.'

In developing this view, approximately one-third of the ample volume is devoted to the subject of egg formation; another third to the physico-chemical and biological (i.e. biochemical) properties of the egg itself; and the last section to its nutritional and industrial uses. In spite of the efforts of the authors to justify their choice of adjectives in the title, it emerges clearly that our precise knowledge of structure and chemistry depends on the egg of exactly one avian species: viz. that biological monstrosity, the domestic fowl. A tremendous amount of factual material has been classified and re-presented with admirable simplicity and clarity of expression: no little merit in a work of this sort. The efforts of the senior author in re-drawing graphs and constructing tables and diagrams contribute considerably to the unity of tone. If some of the section frontispiece diagrams appear a little naive to a professional scientist, they may nevertheless be extremely helpful to a less sophisticated reader.

The bibliography is most impressive, covering European (including of course Slavic), American, and even Asiatic literature in a wide variety of fields. One discovers citations of periodicals ranging from *Quick Frozen Foods* and the *Annales des falsifications et des fraudes*, to the *Proceedings* of the Royal Society and the *Atti* of the *Accademia dei Lincei*. Thus a comprehensive review of technical and scientific literature is achieved: a most useful compilation.

Professor and Mrs. Romanoff are to be congratulated on producing a book which is not only comprehensive within its stated field, but readable. This reviewer would, however, like to offer two suggestions for a future edition: she was most disappointed to find no discussion of the problem of the cuckoo egg; and she would like to see the final anthropological section considerably

expanded. She also suggests that the last plate be done over in colour as a frontispiece. Eggs are not food for the body alone.

D. RUDNICK

PUBLICATIONS RECENTLY RECEIVED

Sweeper in the Sky; by Helen Wright. New York, 1949 (The Macmillan Co., $4.00).

The University of Texas Publication No. 4621. The Ellenburger Group of Central Texas; by Preston E. Cloud, Jr., and V. E. Barnes, Austin, Texas, 1948.

Colloid Chemistry; by H. B. Weiser. 2d Edition. New York, 1949 (John Wiley & Sons, $5.50).

Physics in the Modern World; by Henry Semat. New York, 1949 (Rinehart & Co. Inc., $5.00).

U. S. Geological Survey. Bulletins as follows: 940. Strategic Minerals Investigations, 1943. Price $.05. 944-C. Geology and Ore Deposits of Boise Basin, Idaho; by A. L. Anderson. 945. Strategic Minerals Investigations, 1944. Price $.05. 954-E. Manganese Deposits of the Talamantes District near Parral, Chihuahua, Mexico; by I. F. Wilson and V. S. Rocha. Price $.50. 959-D. Geophysical Abstracts 135 October-December, 1948 (Nos. 10473-10736); by V. L. Skitsky and S. T. Vesselowsky. Price $.25. 960-A. Barite Deposits of a Camamú Bay, State of Bahia, Brazil; by A. J. Bodenlos. Price $.75. 960-B. Antimony Deposits of Soyatal District State of Queretaro, Mexico; by D. E. White. Price $1.00. 960-C. Geology of Tungsten Deposits in North-Central Chile; by J. F. McAllister and Carlos Ruiz F. Price $1.75. 960-E. Geology of Huahuaxtla Mercury District, State of Guerrero, Mexico; by David Gallagher and Rafael Perez Siliceo. Price $.55. 960-D. Tin-Bearing Placers near Guadalcazar, State of San Luis Potosi. Mexico; by Carl Fries, Jr., and Eduardo Schmitter. Price $.50. Professional Papers as follows: 199-B. Mollusca from the Miocene and Lower Pliocene of Virginia and North Carolina. Part 2. Scaphopoda and Gastropoda; by Julia Gardner. Price $.70. 215. Geology of the Southern Guadalupe Mountains, Texas; by P. B. King. Price $3.25. 214-C. Paleocene Fresh-Water Mollusks from Southern Montana; by Teng-Chien Yen. Price $.15.

Bulletin 954-F. Manganese Deposits of Mexico; by P. D. Trask and J. R. Cabo, Jr. Price $.35.

Radioactive Measurements with Nuclear Emulsions; by Herman Yagoda. New York, 1949 (John Wiley & Sons, $5.00).

The Electric-Lamp Industry; by A. B. Bright, Jr. New York, 1949 (The Macmillan Co., $7.50).

The Home University Library of Modern Knowledge. Geology; by H. H. Read. New York and London, 1949 (Oxford University Press, $2.00). The Ocean; by F. D. Ommanney. New York and London, 1949 (Oford University Press, $2.00).

Photoelectricity and Its Application; by V. K. Zworykin and E. G. Ramberg. New York, 1949 (John Wiley & Sons, $7.50).

An Introduction to Crystallography; by F. C. King. New York, 1947 (Longmans, Green & Co., $6.50).

Introduction to Statistical Mechanics; by R. W. Gurney. New York, 1949 (The McGraw-Hill Book Co., $5.00).

The Science of Chemistry; by G. W. Watt and L. F. Hatch. New York, 1949 (The McGraw-Hill Book Co., $4.50).

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